The FRISBEE Tool User Manual

frisbee tool
A software for optimising food quality, energy use and global warming impact of refrigeration
KU LEUVEN
irstea
TNO
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Aérial
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SINTEF
"This software tool has been produced with the financial support of the European Union (grant agreement FP7/2007-2013 – Frisbee).
The results expressed by the use of this tool do by no means reflect the official opinion of the European Union or its representatives."

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A quality, energy and global warming impact assessment tool for chain optimisation

In this document, you will find the following:

- General information
- Installing the FRISBEE tool
- Starting a project
- How to operate the graphical user interface
- How to run a chain optimisation
- How to simulate variability in cold chain

Contact

About the FRISBEE tool

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General information

About the Frisbee project

The Frisbee project is a European Union funded 4-year Project to provide new tools, concepts and solutions for improving refrigeration technologies along the European food cold chain. The objective of the FRISBEE (Food Refrigeration Innovations for Safety, consumers' Benefit, Environmental impact and Energy optimisation along the cold chain in Europe) project is to provide new tools, concepts and solutions for improving refrigeration technologies along the European food cold chain. At all stages the needs of consumer and European industry will be considered. The project will develop new innovative mathematical modelling tools that combine food quality and safety together with energy, environmental and economic aspects to predict and control food quality and safety in the cold chain.

About the FRISBEE tool

The FRISBEE tool is a software for assessing cold chains with respect to quality of products, energy use and the CO_2 emission (environmental) impact of the refrigeration technologies involved in the cold chain. It contains validated kinetic models that can predict how the quality and safety evolve along the cold chain as a function of temperature and duration. Six main product categories have been considered: fruits, ready to eat meal, meat, fish, vegetable and milk products. Furthermore, the Monte Carlo simulation has been implemented

System requirements

The FRISBEE tool is developed within the MatLab environment (The MathWorks, Inc., Natick, MA, USA). From the MatLab program a Windows standalone executable has been compiled which is what is being distributed to the end users. As a result you can use the FRISBEE tool without having MatLab installed on your machine. The FRISBEE tool has been compiled to suit 32 and 64 bit Windows based systems.

License Agreement

The FRISBEE Tool Version 1.1, hence called the FRISBEE Tool, release date July 2015, has been developed in the frame of the EU-FP7-project FRISBEE (Food Refrigeration Innovations for Safety, consumers'Benefit, Environmental impact and Energy optimisation along the cold chain in Europe). The FRISBEE tool Version 1.1 is copyrighted by the nine project partners ("Partners") that have contributed to its development: KU Leuven - Belgium, Irstea - France, TNO - The Netherlands, LSBU - UK, NTUA - Greece, VCBT - Belgium, ADRIA - France, Afverial - France, SINTEF - Norway, collectively called the FRISBEE Tool Consortium.

The FRISBEE Tool is freely available for download by any interested party upon acceptance of this license agreement. The FRISBEE Tool can only be used for simulating and optimizing the sustainability indicators (namely, quality and safety, energy use and global warming potential) associated with refrigeration technologies in the agri-food cold chain for the food products included in this version 1.1.

Any other use of the FRISBEE tool, any part thereof or its underlying code, is prohibited.

While every attempt has been made to ensure the reliability of the FRISBEE Tool, the FRISBEE Tool Consortium, its Partners or their employees cannot be held responsible for any errors or omissions, or for the results obtained from the use of the FRISBEE tool. The FRISBEE tool is provided "as is", with no guarantee of completeness, accuracy, timeliness or for the results obtained from the use of this information, and without warranty of any kind, express or implied, including, but not limited to warranties of performance, merchantability and fitness for a particular purpose. In no event will the FRISBEE Tool Consortium, its Partners or their employees, be liable for any decision made or action taken in reliance on the information provided by the FRISBEE tool or for any consequential, special or similar damages. By downloading the FRISBEE Tool you accept to indemnify and hold harmless the FRISBEE Tool Consortium, its Partners or their employees against any claim of a third party against the FRISBEE Tool Consortium or against any one of the Partners or its employees, in as far such claim results from your use of the FRISBEE Tool.

On publishing or presenting the results obtained with the FRISBEE tool, the following citation should be included: S.G. Gwanpua, P. Verboven, D. Leducq, T. Brown, B.E. Verlinden, E. Bekele, W. Aregawi, J. Evans, A. Foster, S. Duret, H.M. Hoang, S. van der Sluis, E. Wissink, L.J.A.M. Hendriksen, P. Taoukis, E. Gogou, V. Stahl, M. El Jabri, J.F. Le Page, I. Claussen, E. Indergard, B.M. Nicolai, G. Alvarez, and A.H. Geeraerd, 2015. Journal of Food Engineering, Volume 148, Pages 2-12. doi:10.1016/j.jfoodeng.2014.06.021. Additional research publications related to specific parts of the FRISBEE tool that you may be using, should be referenced using the appropriate citation(s). A full list of bibliographic references is provided in the FRISBEE Tool User Manual and on the FRISBEE Tool website.

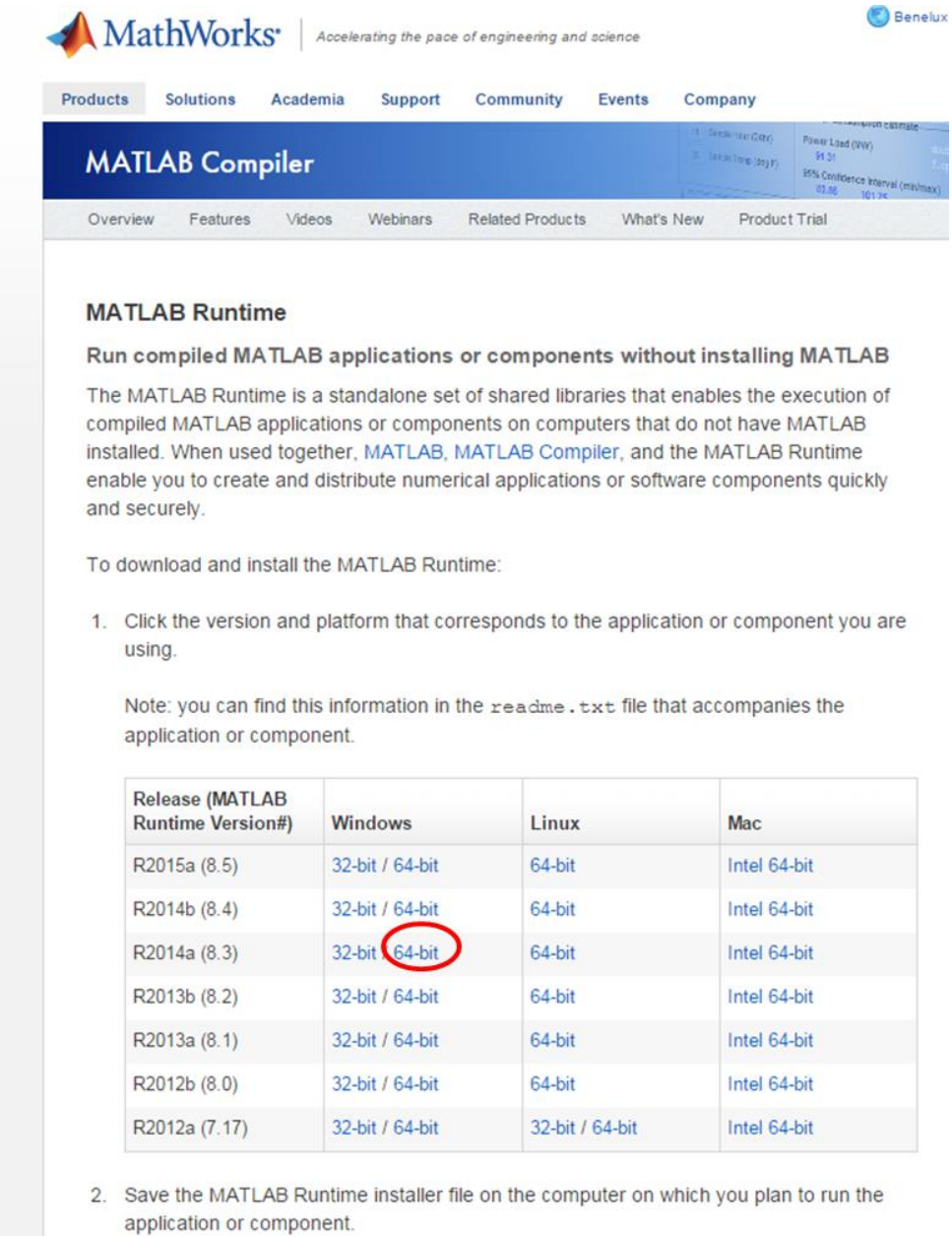
Questions, remarks and suggestions regarding the FRISBEE Tool are welcomed at info@frisbeetool.eu

Installing the FRISBEE tool

The FRISBEE tool is fully tested only in Windows 64 bit environment.

Install the freeware MCR Installer

To be able to run the FRISBEE tool, you must *first* install the MCRInstaller.
(In the unlikely event of having already an older versions of the MCRInstaller on your PC, this older version should be removed first. Please verify with your IT manager how to properly remove it.)
Go to the website http://www.mathworks.nl/products/compiler/mcr/index.html
Download the 2014a version corresponding to 64-bit.



Follow the instructions on the website and on the installer. Please note that you need to have administrator rights on your PC to enable installation. The whole process may take 10 minutes or even more, depending on your system specifications.

Functionalities

Functionalities
The user can select between a number of representative food products
The user can select a reference cold chain for each product
The user can build a tailor-made cold chain using representative cold chain blocks
Simulation of quantified CO_2 emissions is possible for a selected cold chain (reference or tailor-made)
Simulation of static energy use (in kWh/kg) is possible for a selected cold chain (reference or tailor-made)
All quality indicators relevant for the specific food product can be simulated for a selected cold chain (reference or tailor-made)
A user can change properties of a selected product, and also settings of cold chain block technologies
Heat and mass transfer models are available for describing temperature and moisture heterogeneity
The user can simulate alternative cold chains using representative cold chain blocks. The following new technologies are implemented: superchilling, supercooling, VIP in walls, PCM
Simulation of energy use for new and emerging technologies for: superchilling and supercoiling, VIP in walls and PCM
Monte Carlo simulation
Dynamic energy use models are being used
Model reduction techniques are implemented
Simplified temperature model is being used
Multi-objective optimization
Objective technology selection algorithm

FRISBEE Tool citation

Gwanpua, S., Verboven, P., Leducq, D., Brown, T., Verlinden, B., Bekele, E., Aregawi, W., Evans, J., Foster, A., Duret, S., Hoang, H., van der Sluis, S., Wissink, E., Hendriksen, L., Taoukis, P., Gogou, E., Stahl, V., El Jabri, M., Lepage, J., Claussen, I., Indergård, E., Nicolai, B., Alvarez, G., Geeraerd, A. (2015). The FRISBEE tool, a software for optimising the trade-off between food quality, energy use, and global warming impact of cold chains. Journal of Food Engineering, 148, 2-12. doi:10.1016/j.jfoodeng.2014.06.021.

Additional research publications related to the FRISBEE Tool

- Evans, J., and Alvarez, G., 2015. Cold Chain refrigeration innovations the FRISBEE project. Journal of Food Engineering, Volume 148, Pages 1

- Couvert, O., Pinon, A., Bergis, H., Bourdichon, F., Carlin, F., Cornu, M., Denis, C., Gnanou Besse, N., Guillier, L., Jamet, E., Mettler, E., Stahl, V., Thuault, D., Zuliani, V. Augustin, J.-C., 2010. Validation of a stochastic modelling approach for *Listeria monocytogenes* growth in refrigerated foods, International Journal of Food Microbiology, 144 (2), 236-242.
- Dermesonluoglu, E., Katsaros, G., Tsevdou, M., Giannakourou, M., Taoukis, P., 2015. Kinetic study of quality indices and shelf life modelling of frozen spinach under dynamic conditions of the cold chain. Journal of Food Engineering, Volume 148, Pages 13–23
- Gwanpua, S., Verlinden, B.E, Hertog, M.L.A.T.M., Nicolai, B.M., Geeraerd, A.H., 2014. Managing biological variation in skin background colour along the postharvest chain of Jonagold apples. Postharvest Biology and Technology 93, 61-71.
- Gwanpua, S., Verlinden, B.E, Hertog, M.L.A.T.M., Van Impe, J., Nicolaï, B.M., Geeraerd, A.H., 2013. Towards flexible management of postharvest variation in fruit firmness of three apple cultivars. Postharvest Biology and Technology 85, 18–29.
- Pouillot, R., Albert, I., Cornu, M., Denis, J.B., 2003. Estimation of uncertainty and variability in bacterial growth using Bayesian inference. Application to Listeria monocytogenes. International Journal of Food Microbiology, 81 (2), 87–104
- Stahl, V., Ndoye, F.T., El Jabri, M., Le Page, J. F., Hezard, B., Lintz, A.,. Geeraerd, A.H, Alvarez, G., Thuault, D., 2015. Safety and quality assessment of ready-to-eat pork products in the cold chain,Journal of Food Engineering, Volume 148, Pages 43-52
- Tsevdou, M., Gogou, E., Dermesonluoglu, E., Taoukis, P., 2015. Modelling the effect of storage temperature on the viscoelastic properties and quality of ice cream. Journal of Food Engineering, Volume 148, Pages 35-42
- Ndoye, F.T., Alvarez, G., 2015. Characterization of ice recrystallization in ice cream during storage using the focused beam reflectance measurement. Journal of Food Engineering, Volume 148, Pages 24-34
- Duret, S., Gwanpua, S., Hoang, H., Guillier, L., Flick, D., Laguerre, O., Verlinden, B., De Roeck, A., Nicolai, B., Geeraerd, A., 2015. Identification of the significant factors in food quality using global sensitivity analysis and the accept-and-reject algorithm. Part III: Application to the apple cold chain. Journal of Food Engineering, 148, 66-73.
- Duret, S., Gwanpua, S., Hoang, H., Guillier, L., Flick, D., Laguerre, O., El Jabri, M., Thuault, D., Hezard, B., Lintz, A., Stahl, V., Geeraerd, A., 2015. Identification of the significant factors in food quality using global sensitivity analysis and the accept-and-reject algorithm. Part II: Application to the cold chain of cooked ham. Journal of Food Engineering, 148, 58-65.
- Duret, S., Gwanpua, S., Hoang, H., Guillier, L., Flick, D., Geeraerd, A., Laguerre, O., 2015. Identification of the significant factors in food quality using global sensitivity analysis and the accept-and-reject algorithm. Part I: Methodology. Journal of Food Engineering, 148, 53-57.
- Stonehouse, G.G., Evans, J.A., 2015. The use of supercooling for fresh foods: A review. Journal of Food Engineering, 148, 74-79.

Running the FRISBEE tool

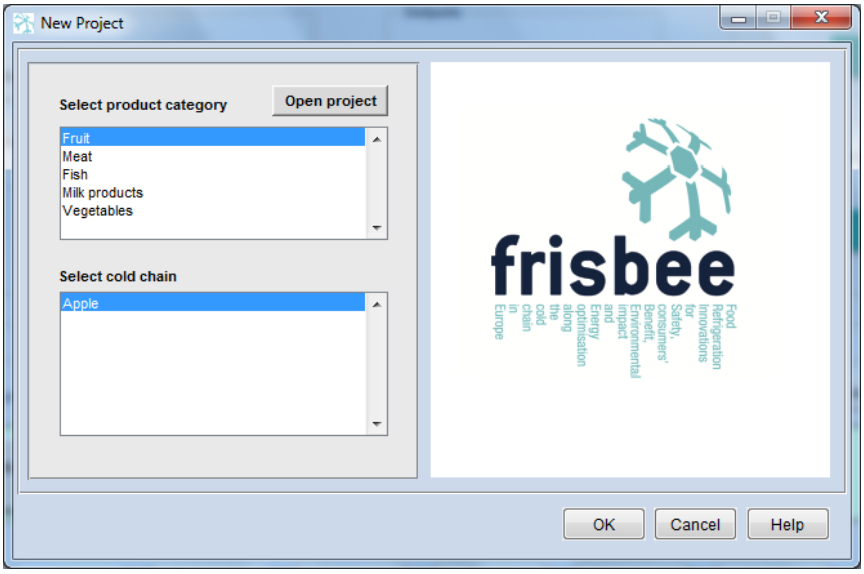
In this section, you will learn to do the following using the FRISBEE tool:

- How to start a project
- How to build a cold chain
- How to modify cold chain block's properties
- How to start a chain simulation simulation
- How to view and manipulate results

Starting a project

Step 1. Run FrisbeeTool.exe.

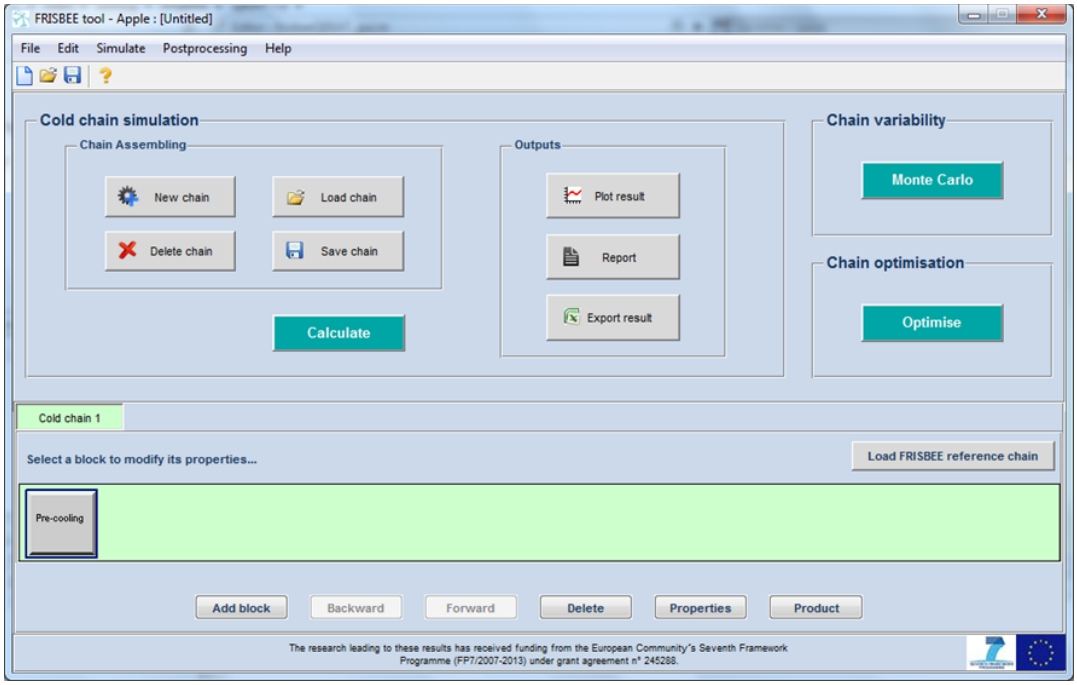
The following window appears



Step 2. Selecting a cold chain;

- Select a product from the product categories, e.g. Meat
- Select a cold chain, e.g. Raw smoked and salted ham-like bacon.

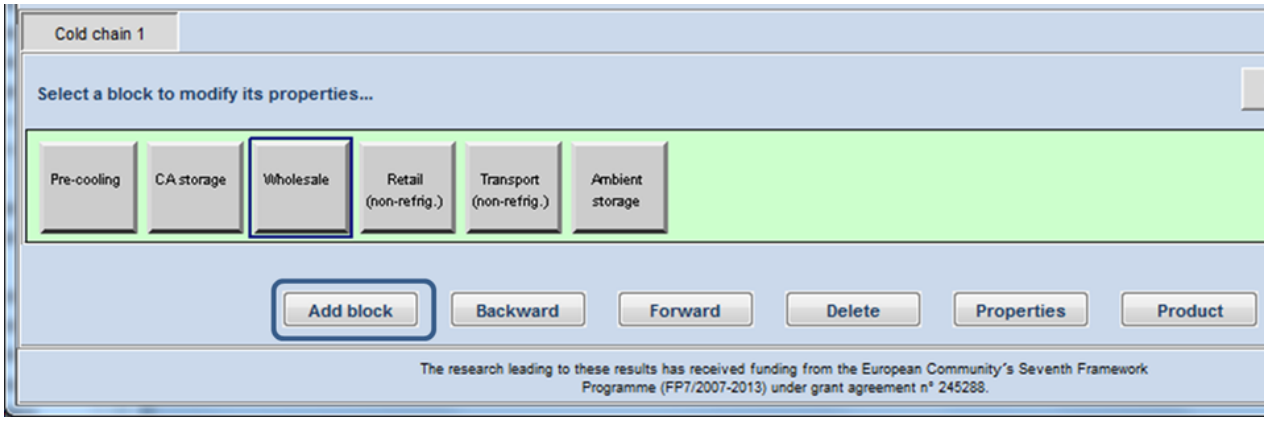
Step 3. Click OK. The reference cold chain settings will be loaded, and the main environment of the QEEAT will open.



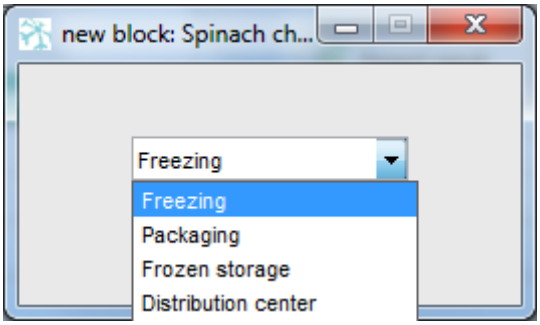
Main working environment of the FRISBEE Tool

Building a cold chain

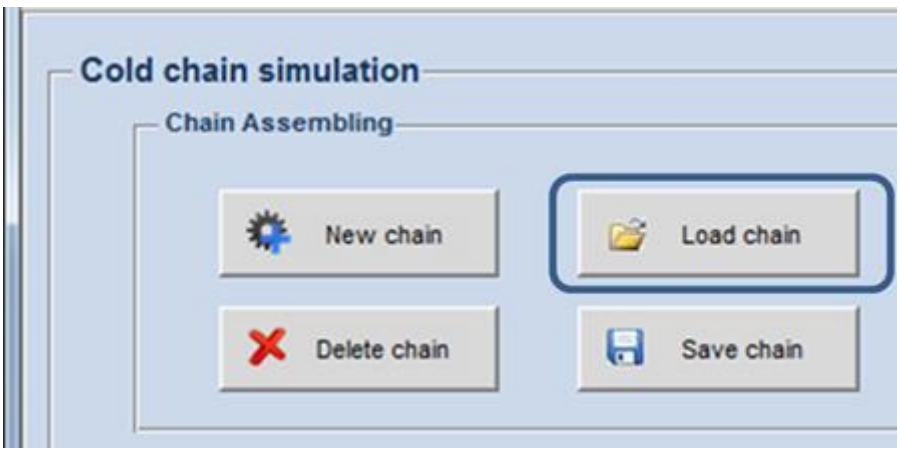
- Once a project is started, cold chain blocks can be added using the **Add blocks** button



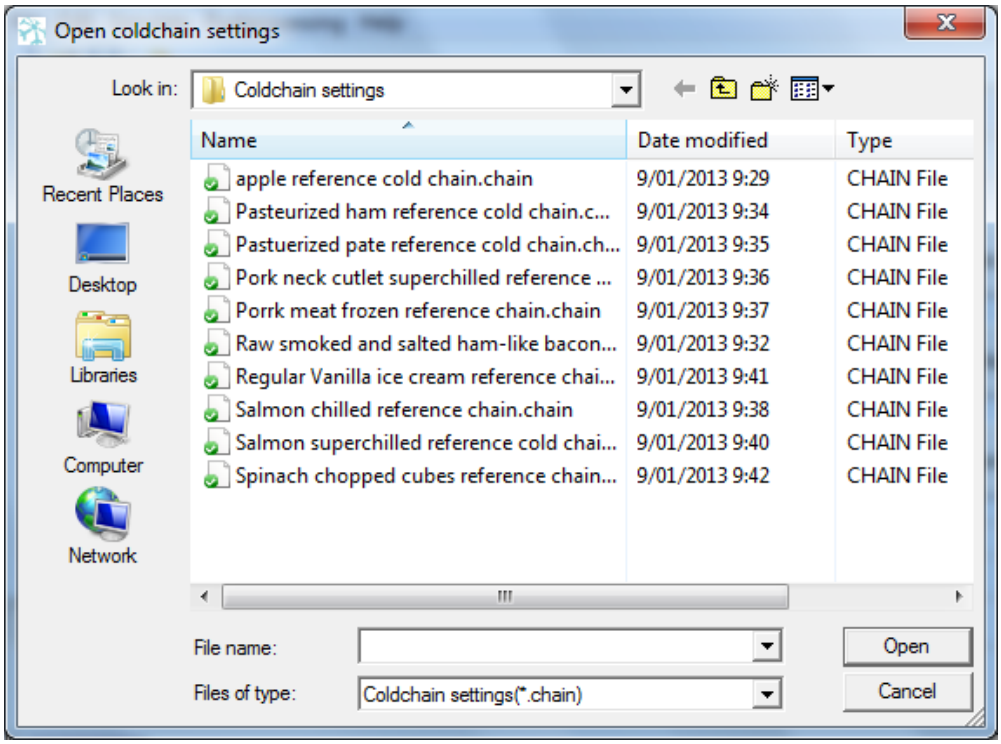
- The user can select cold chain blocks from list of default cold chain blocks. Note that these cold chain blocks are cold chain specific.



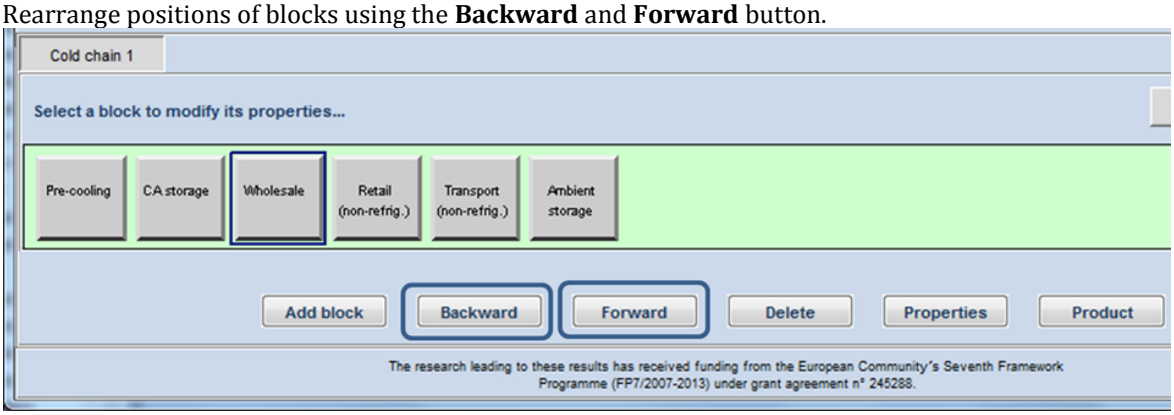
- The user can load saved cold chain (e.g. the reference cold chain) using **Load chain** button



- Load existing cold chain (e.g. reference cold chain) from any directory


Open coldchain settings
Look in:
Coldchain settings
Recent Places
Desktop
Libraries
Computer
Network
Name
Date modified
Type
apple reference cold chain.chain 9/01/2013 9:29 CHAIN File
Pasteurized ham reference cold chain.c... 9/01/2013 9:34 CHAIN File
Pastuerized pate reference cold chain.ch... 9/01/2013 9:35 CHAIN File
Pork neck cutlet superchilled reference ... 9/01/2013 9:36 CHAIN File
Porrk meat frozen reference chain.chain 9/01/2013 9:37 CHAIN File
Raw smoked and salted ham-like bacon... 9/01/2013 9:32 CHAIN File
Regular Vanilla ice cream reference chai... 9/01/2013 9:41 CHAIN File
Salmon chilled reference chain.chain 9/01/2013 9:38 CHAIN File
Salmon superchilled reference cold chai... 9/01/2013 9:40 CHAIN File
Spinach chopped cubes reference chain... 9/01/2013 9:42 CHAIN File
File name:
Files of type:
Coldchain settings(*.chain)
Open
Cancel

- Rearrange positions of blocks using the **Backward** and **Forward** button.



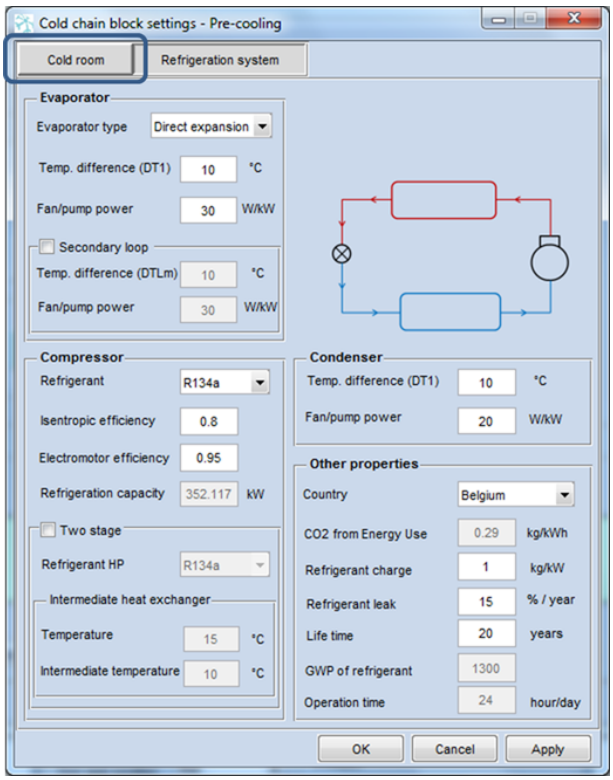
- Delete cold chain blocks using the **Delete** button. The selected block will be deleted

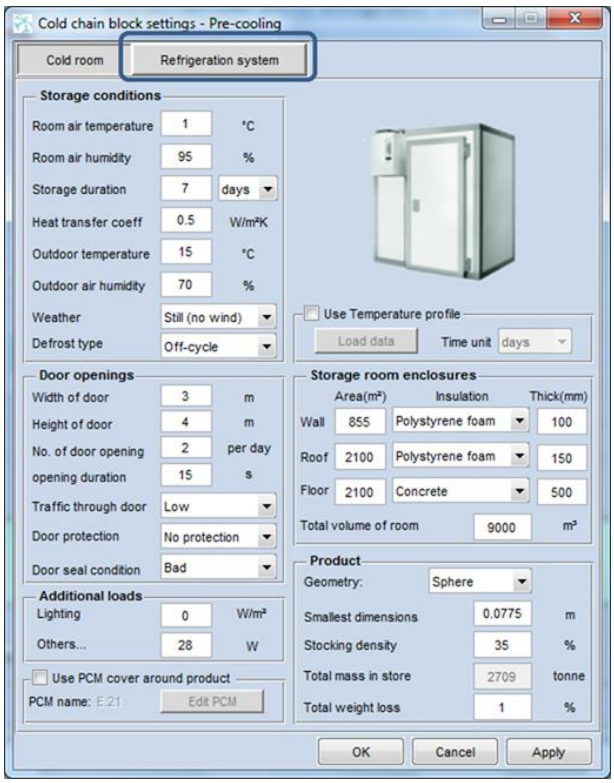
Modifying cold chain block's properties

- To make modifications in a cold chain block (e.g. set points, chain duration, refrigerant type, efficiencies etc.), *double click* on the block or select the block and click on **Properties**.

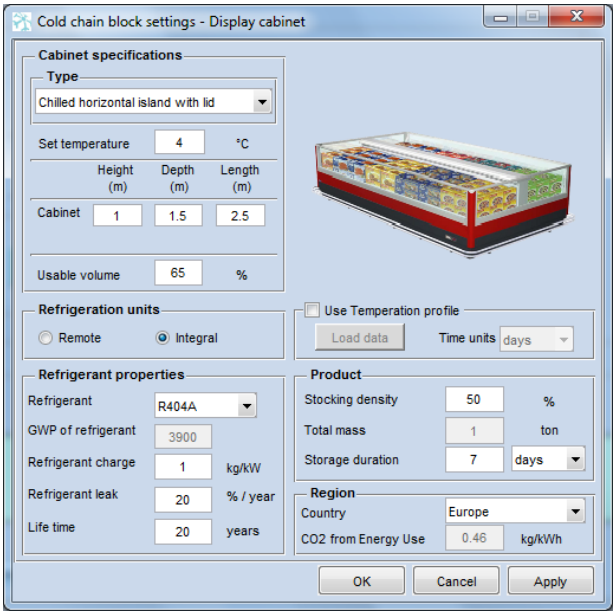
Add block
Backward
Forward
Delete
Properties
The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 245288.

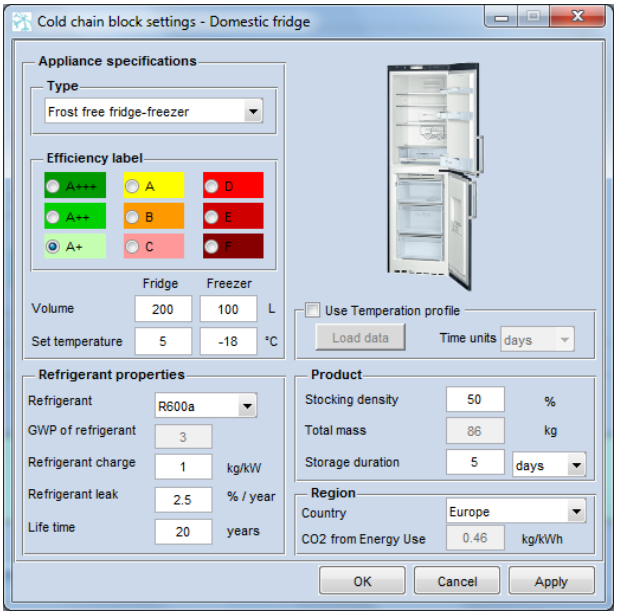
- This action opens the property window, which has two main tabs: the **Cold room** tab for modifying properties of the cold room, and the **Refrigeration system** tab for modifying properties of the refrigeration system



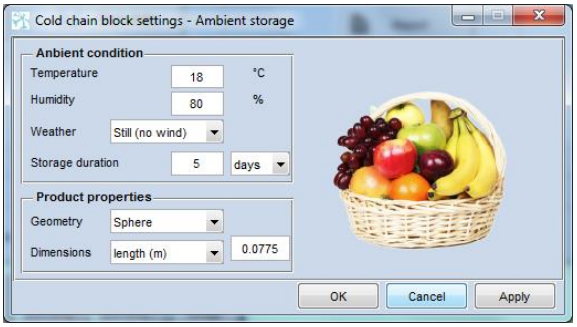


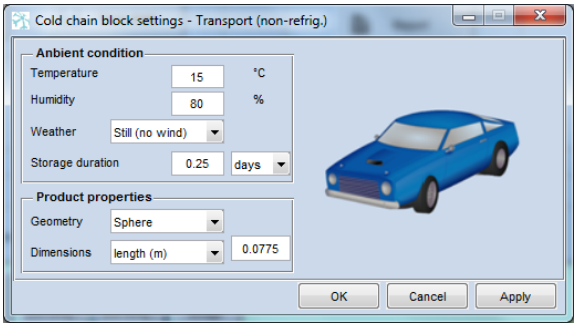
- For Domestic fridge, Display cabinets (Super market), and non refrigerated processes, the Properties windows are different from the other standard blocks





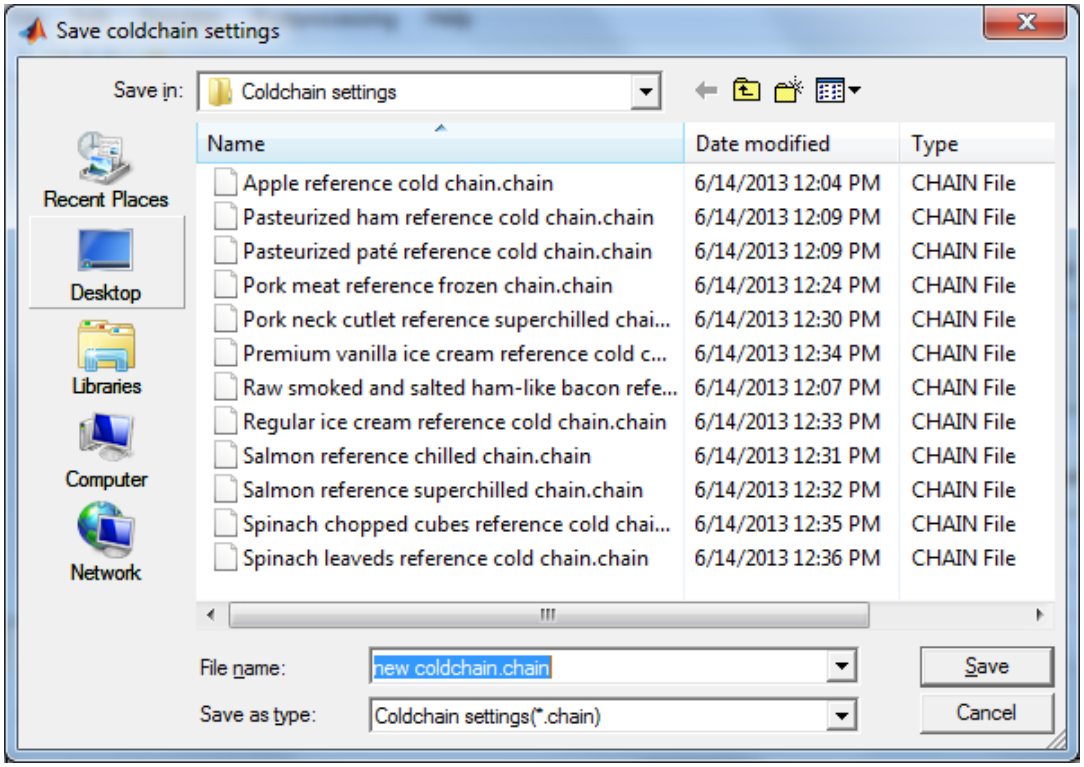
- For non refrigerated processes such as storage on shelf, or transport, the user is required only to provide ambient conditions and duration, without any need for information on the technology



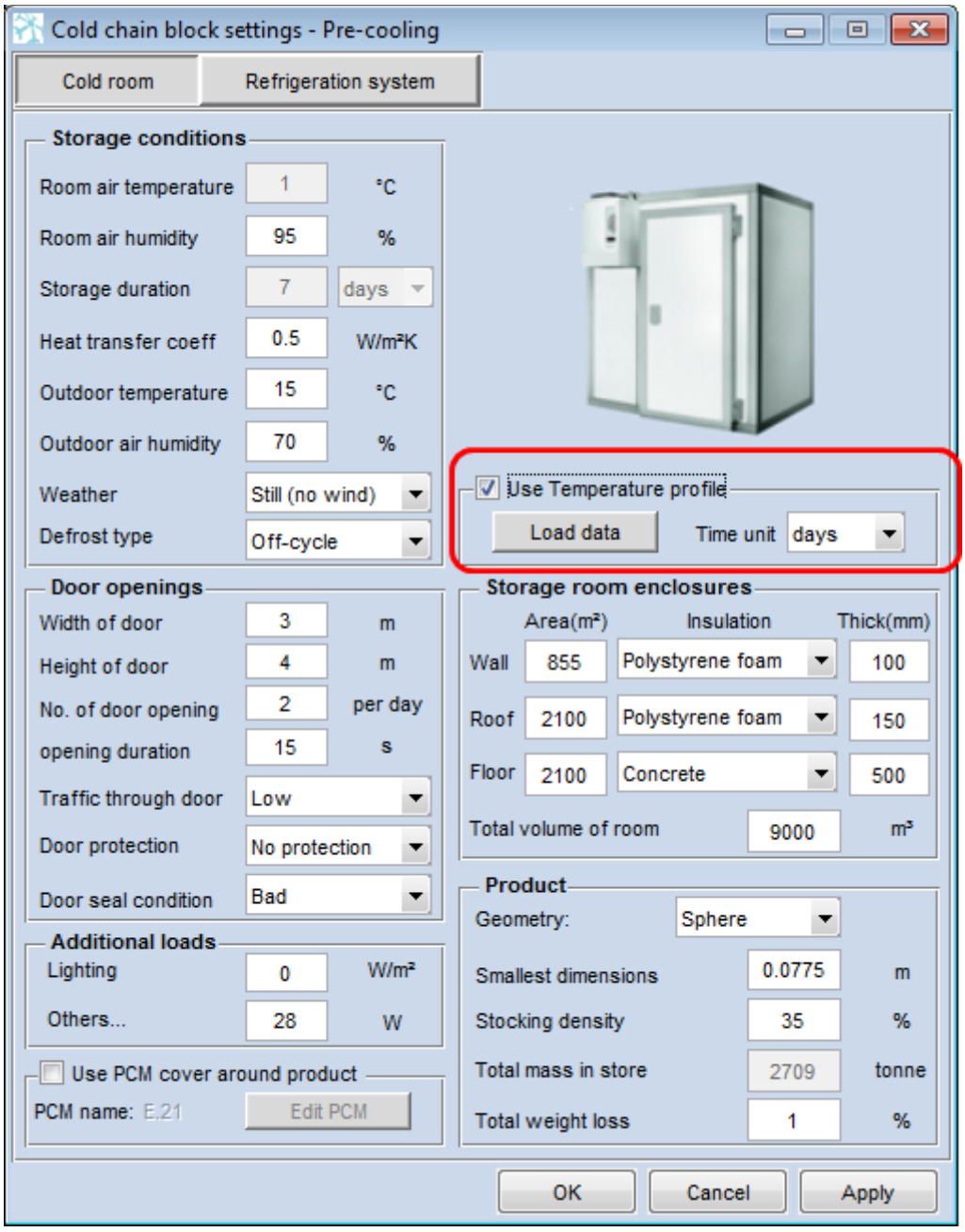


- Once all changes have been made, select **OK** to apply changes. This action will close the Properties window.
- When the chain has been built completely, you can save the cold chain using the **Save chain** button

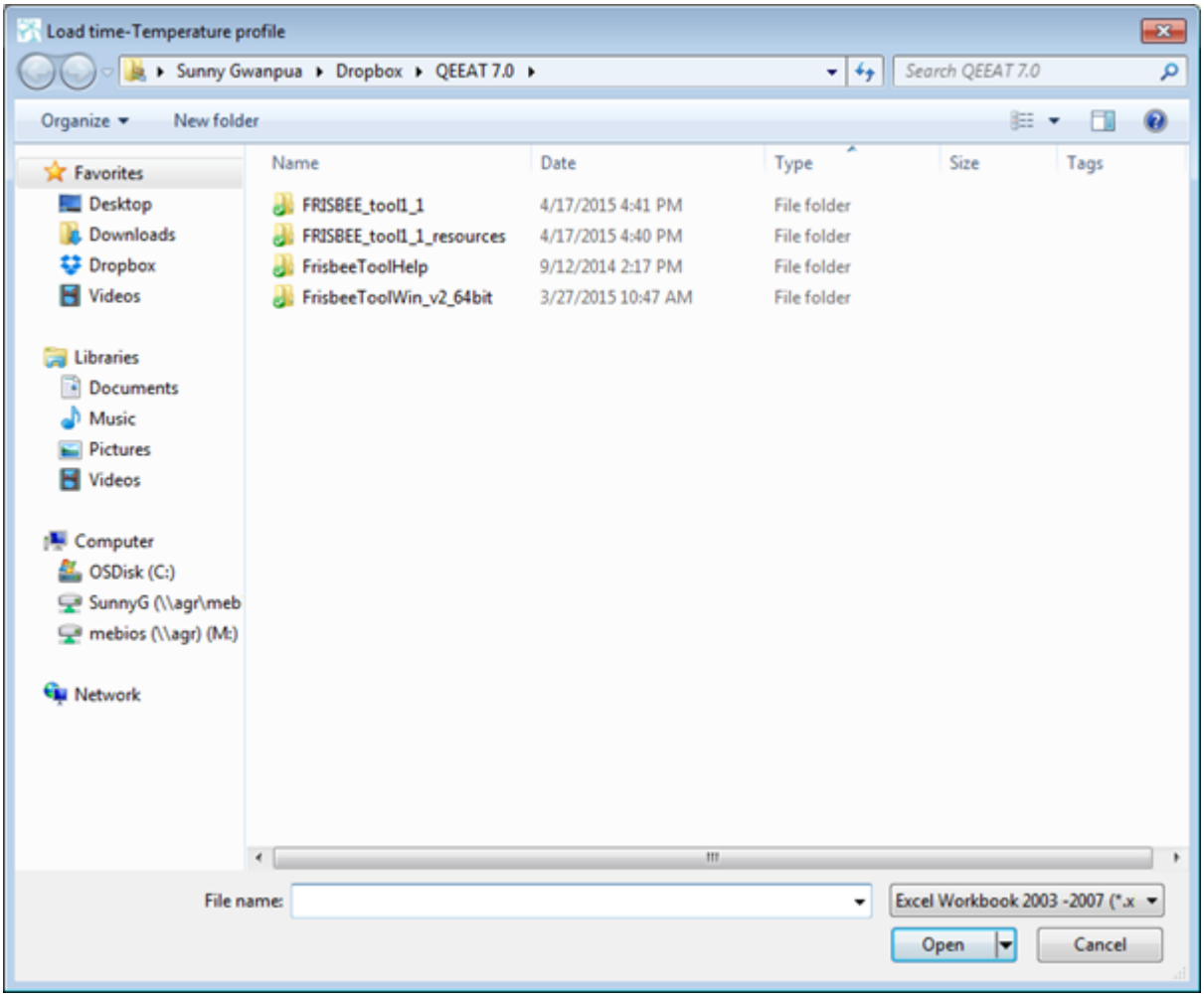
- The save dialogue box opens, asking you to give a name to your chain and also to select a location to **Save chain**.


Save coldchain settings
Save in:
Coldchain settings
Recent Places
Desktop
Libraries
Computer
Network
Name
Date modified
Type
Apple reference cold chain.chain 6/14/2013 12:04 PM CHAIN File
Pasteurized ham reference cold chain.chain 6/14/2013 12:09 PM CHAIN File
Pasteurized paté reference cold chain.chain 6/14/2013 12:09 PM CHAIN File
Pork meat reference frozen chain.chain 6/14/2013 12:24 PM CHAIN File
Pork neck cutlet reference superchilled chai... 6/14/2013 12:30 PM CHAIN File
Premium vanilla ice cream reference cold c... 6/14/2013 12:34 PM CHAIN File
Raw smoked and salted ham-like bacon refe... 6/14/2013 12:07 PM CHAIN File
Regular ice cream reference cold chain.chain 6/14/2013 12:33 PM CHAIN File
Salmon reference chilled chain.chain 6/14/2013 12:31 PM CHAIN File
Salmon reference superchilled chain.chain 6/14/2013 12:32 PM CHAIN File
Spinach chopped cubes reference cold chai... 6/14/2013 12:35 PM CHAIN File
Spinach leaveds reference cold chain.chain 6/14/2013 12:36 PM CHAIN File
File name:
new coldchain.chain
Save as type:
Coldchain settings(*.chain)
Save
Cancel

- The temperature profile can be loaded into the FRISBEE tool via the cold chain block settings window.



- The time must be the first column, and the temperature the second column. also, the time must be monotonically increasing. Data format accepted are .xls, .xlsx, and .csv.
- To load data, click on the **Load data** button. This button is only enabled when the **Use Temperature profile** checkbox is checked.

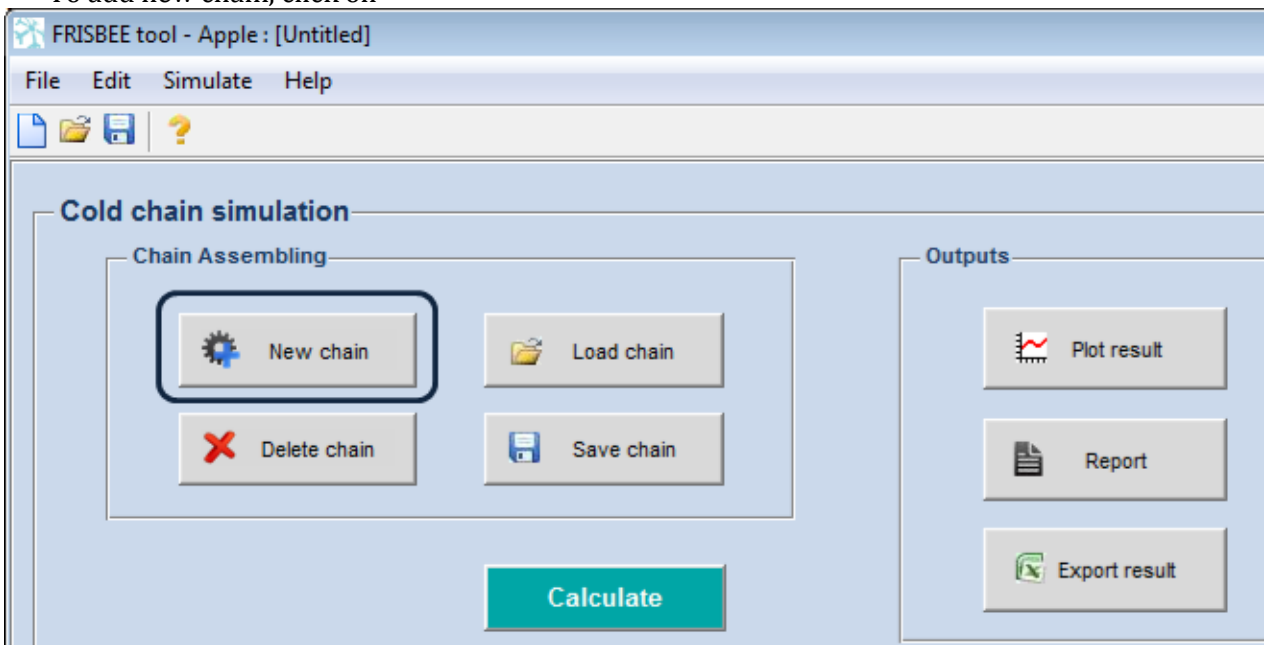


- Select temperature profile file, and click **Open**.

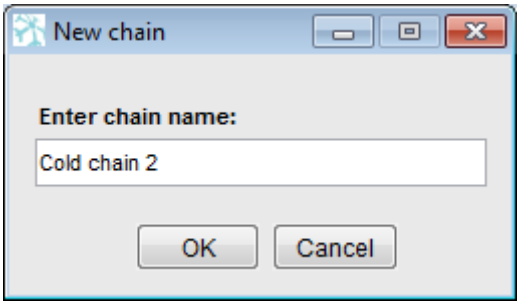
NB:
The energy use and CO2 emission calculations for a cold chain block in which the temperature profile has been loaded is based on assumption of a steady state temperature equal to the weighted average of the temperature profile. This should not be relied upon. Our advice is use temperature profile only to simulate quality.

Adding new chains

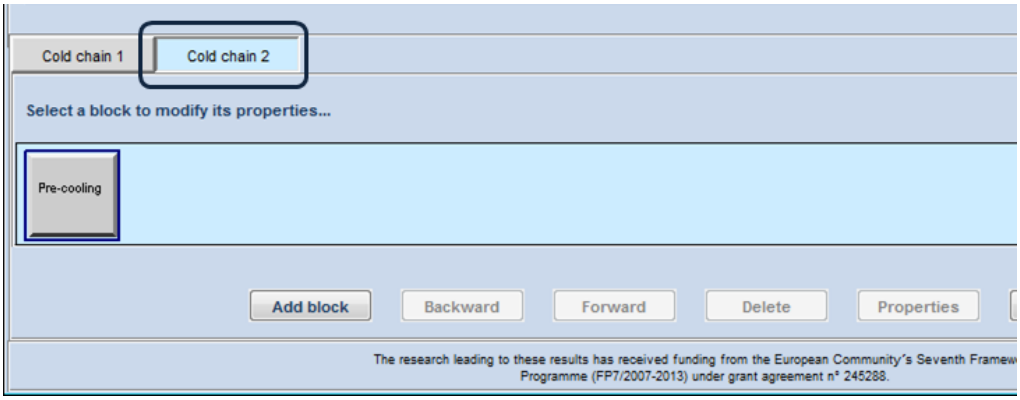
- With the FRISBEE Tool, up to 6 cold chains can be built and simulated at once. This offer the possibilities of comparing several cold chain scenarios.
- To add new chain, click on



- A dialogue Window opens, from which the name of the cold chain can be entered.

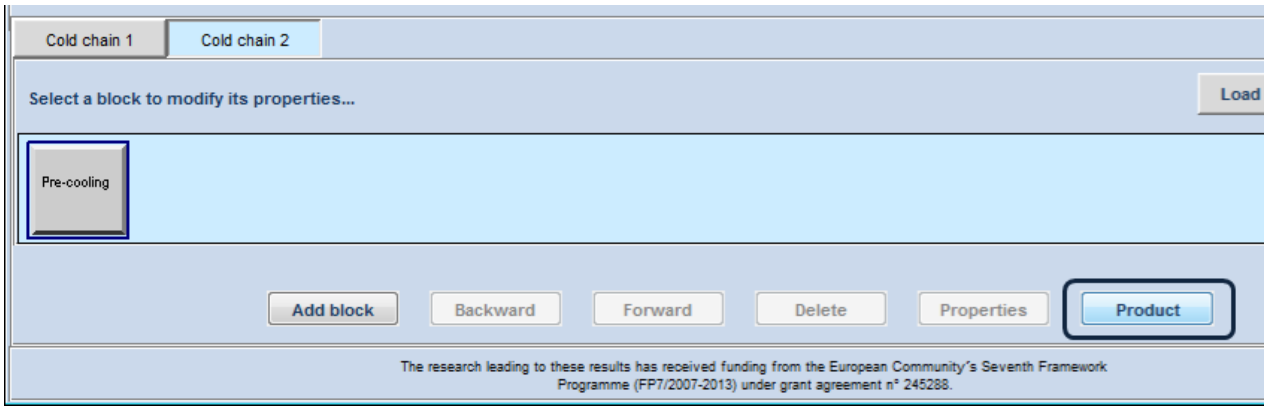


- Once the name of the cold chain is entered, click OK. A new chain is added, with the first block added by default. The first block is the starting block for the reference cold chain.

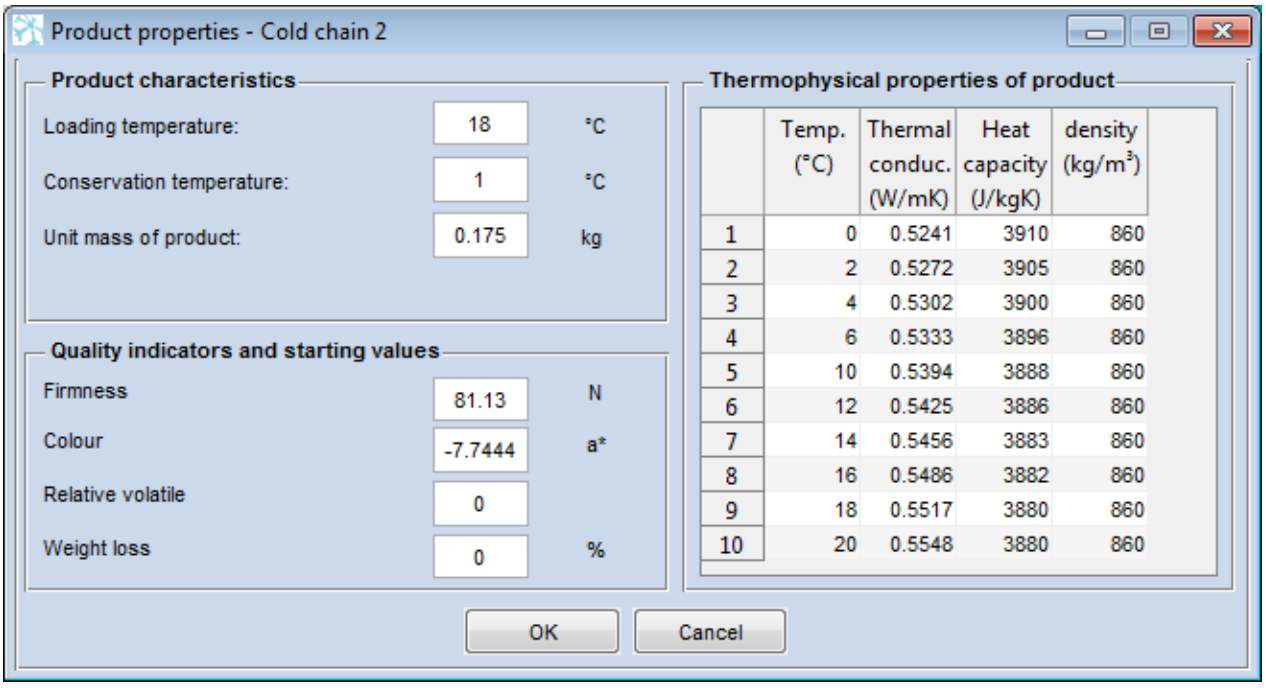


Modifying product properties

- The product properties within each cold chain can be modified by clicking on the "Product" button at the bottom of the cold chain blocks.



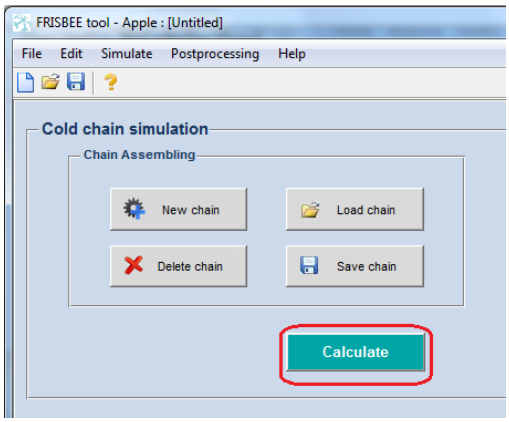
- The "Product property" window opens. This window display the product characteristics: loading product temperature (temperature at which the product entered the cold chain), the conservation temperature, the unit mass of the product. These properties can be changed by the user, simply by entering other values.


Product properties - Cold chain 2
Product characteristics
Loading temperature: 18 °C
Conservation temperature: 1 °C
Unit mass of product: 0.175 kg
Quality indicators and starting values
Firmness 81.13 N
Colour -7.7444 a*
Relative volatile 0
Weight loss 0 %
Thermophysical properties of product
Temp. (°C) | Thermal conduc. (W/mK) | Heat capacity (J/kgK) | density (kg/m³)
1 0 0.5241 3910 860
2 2 0.5272 3905 860
3 4 0.5302 3900 860
4 6 0.5333 3896 860
5 10 0.5394 3888 860
6 12 0.5425 3886 860
7 14 0.5456 3883 860
8 16 0.5486 3882 860
9 18 0.5517 3880 860
10 20 0.5548 3880 860
OK
Cancel

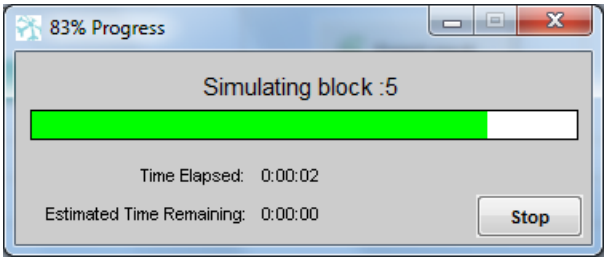
- Additionally, the starting values of the quality indicators can be modified by the user. finally, the thermophysical properties are also displayed, although these values cannot be changed by the user.

Chain simulations

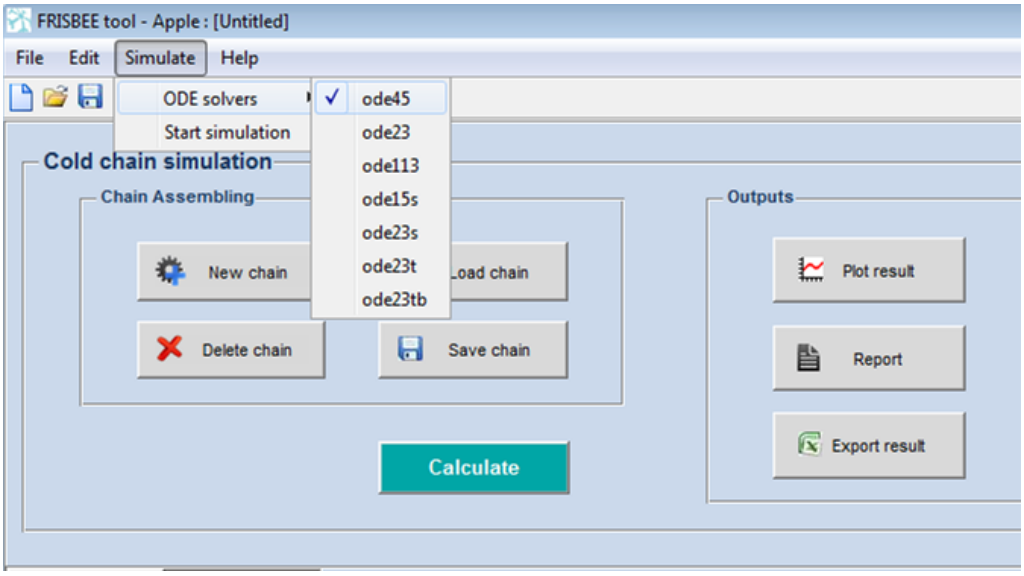
- Click on **Calculate** button to simulate cold chain.



- The software will simulate the energy use, CO2 emission and quality evolution along the cold chain(s). note that it is possible to build more than one chain (up to six chains can be added) and run all simulations at once.



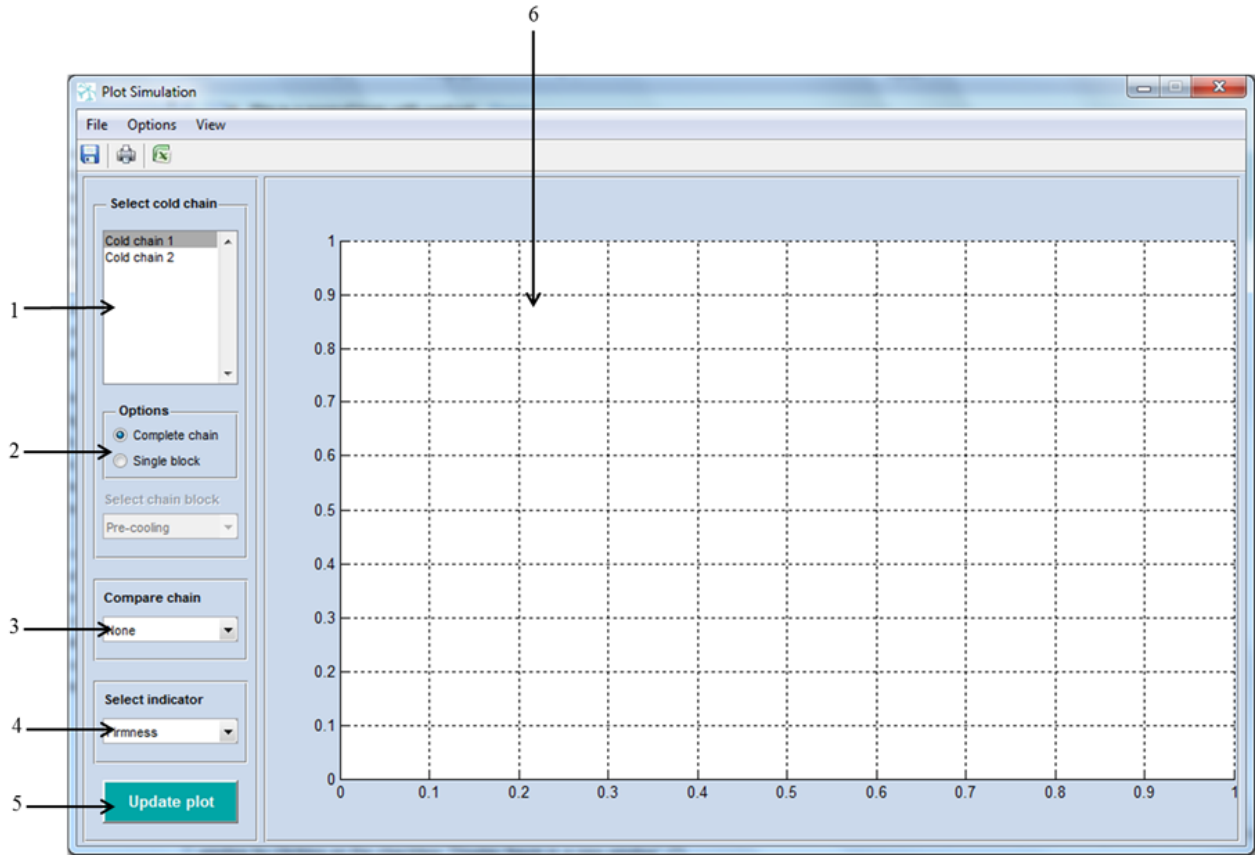
- If the simulation is too slow, or if the simulation gets interrupted, try other ODE solver. This is particular important when running simulations involving temperature profile. Different ODE solvers can be selected



Plots

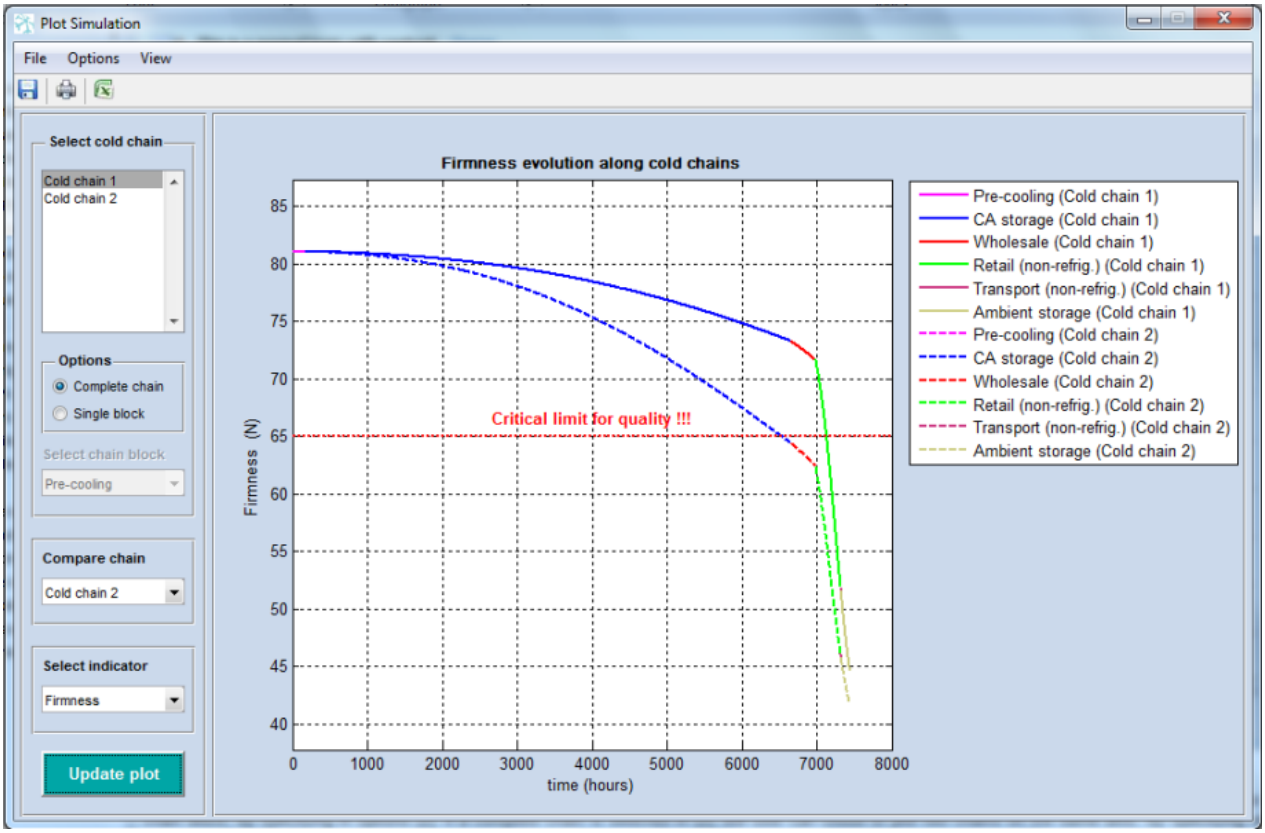
Plotting chain simulations

Once the simulation is completed, the plot windows pops open. The plot Window can also be called from the main GUI, but this will give an error message if a user attempts to call the plot window without first performing any simulations.
The Plot window is shown below:

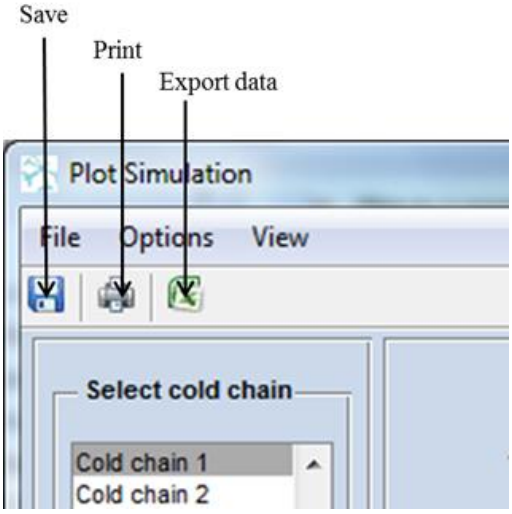


All chains that were simulated are displayed in (1), from which the user can select which chain to plot. The user can also chose to plot the simulations for a single cold chain block, by specifying in options (2). If a complete chain is selected in (2), the user can chose to plot two chains on the same axis, by specifying which chain to compare with in (3). For any plot, the indicator must be specified in (4). This can be one the quality indicators, energy use, CO_2 emission, or product core temperature.
When all selections have been made, the use can then display plot by clicking on "Update plot" (5). The plot(s) is then display on (6).

For example, the figure below shows the firmness of two cold chain scenarios.

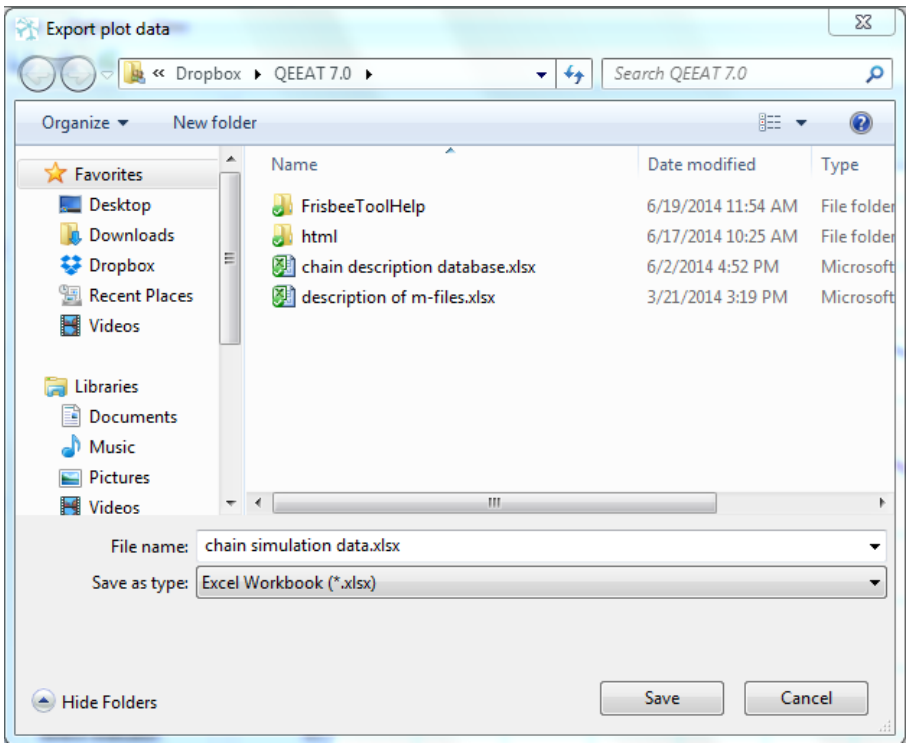


From the **File** menu or the tool bar in the figure plot, a user can chose to save plot, print plot, or export the plot data.



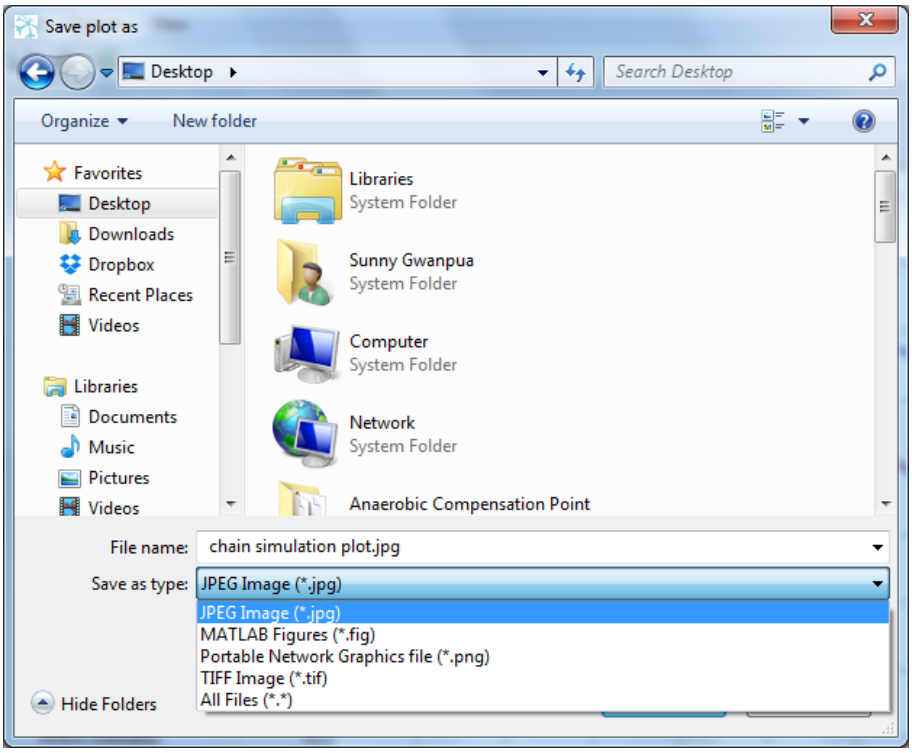
Export plot data

The plot data can be exported to an excel data file by clicking on the Export data icon on the plot tool bar. A dialogue box opens, requested the user to specify where to store data.



Save plot figure

The plot can be saved as an image file (png, tiff, jpg) or a Matlab figure



Print figure

Send a print command for the plot by selecting Print figure

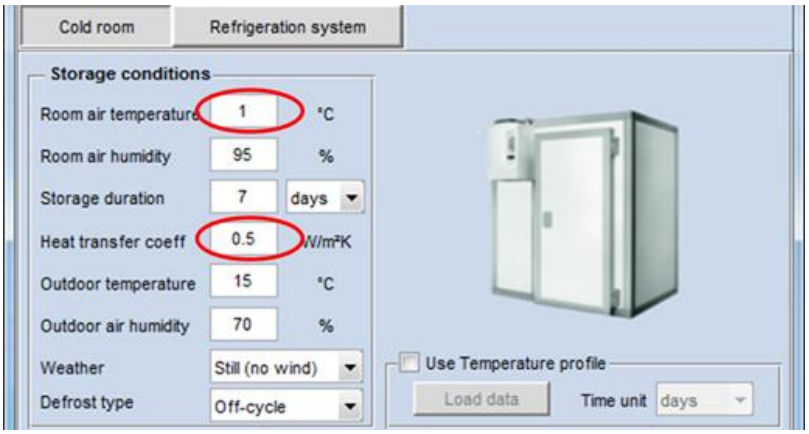
Emerging technologies

The following new and emerging technologies have been implemented in the FRISBEE tool

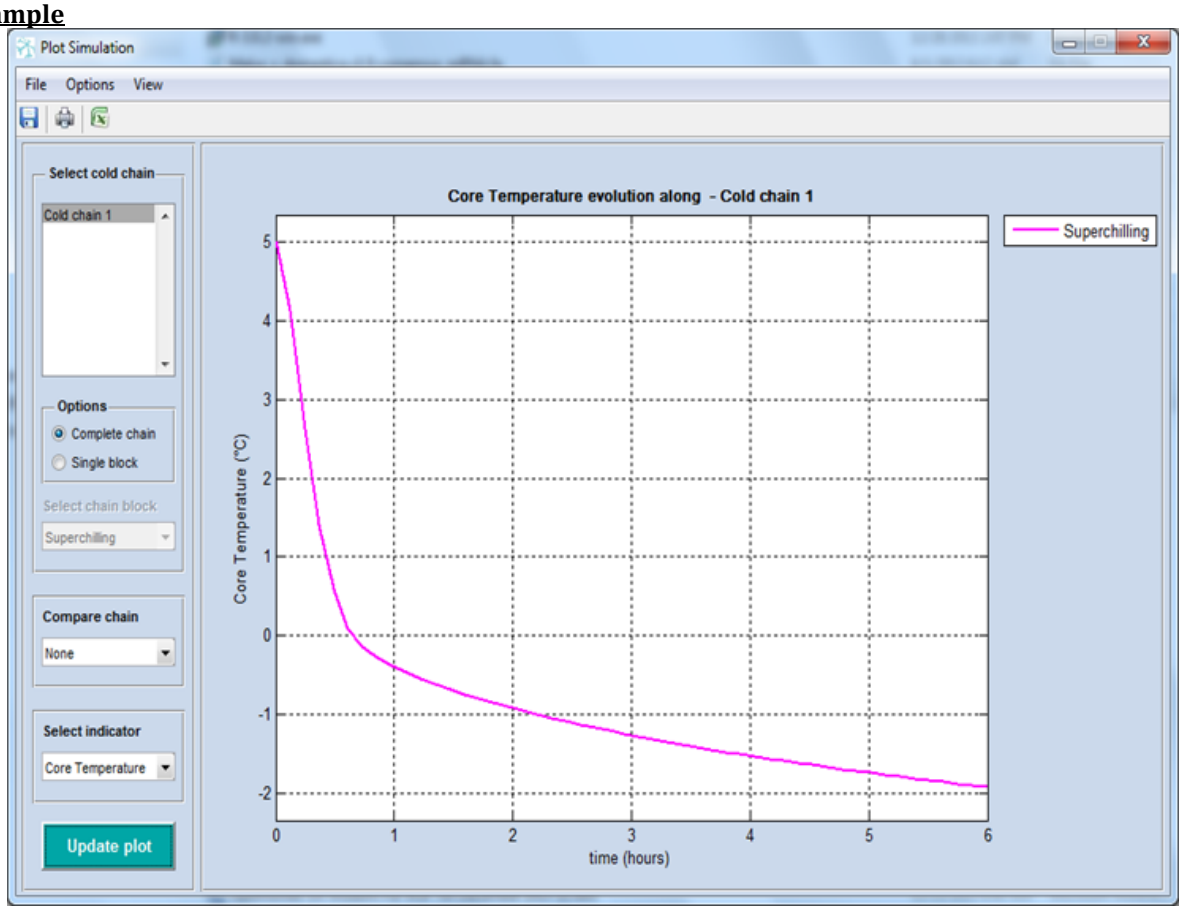
- Simulations of superchilling and supercooling processes
- The use of Vacuum Insulation Panels (VIPs) in the walls of cold rooms
- The use of Phase Change Materials (PCMs) covering around food

Superchilling and supercooling

A product heat and mass transfer model has been implemented in the FRISBEE tool.
To achieve superchilling and supercooling, the user can play around the cooling rate.
To achieve this in the FRISBEE tool, the user can specify different values for the heat transfer coefficient and air temperature, using the properties window.



Example

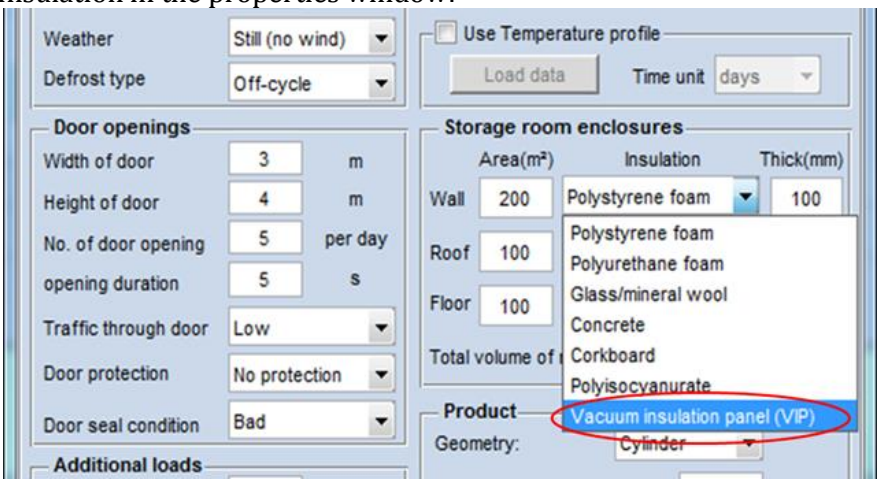


Graphical output from FRISBEE tool. chain simulations showing product temperature.

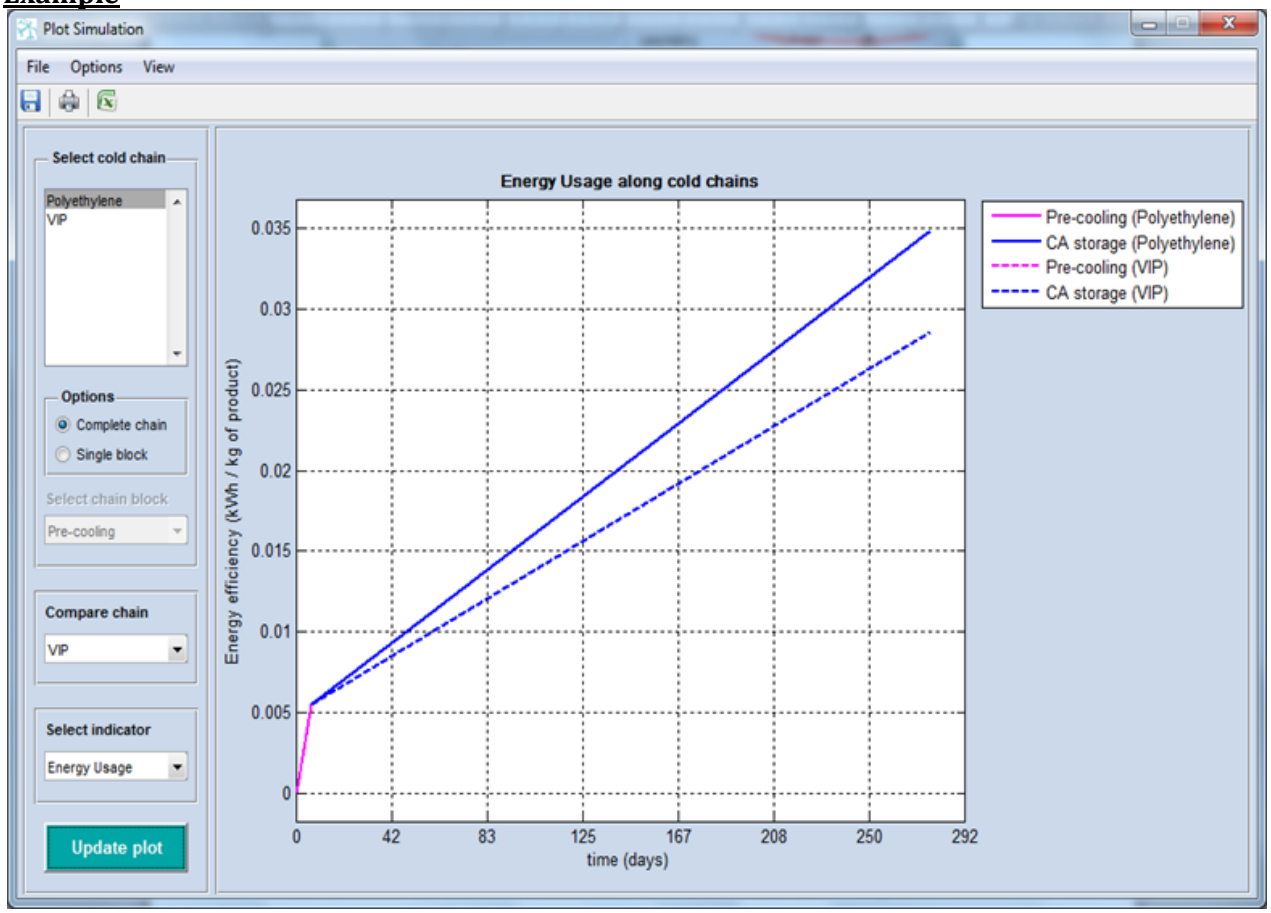
Use of Vacuum Insulation Panels (VIPs)

Vacuum Insulation Panel (VIP) in walls

VIP in walls can be simulated using the FRISBEE tool by selecting Vacuum Insulation Panel (VIP) from the list of Insulation in the properties window:



Example

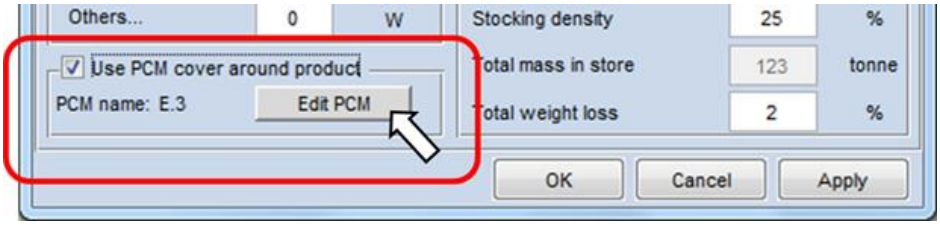


Graphical output from FRISBEE tool chain simulations during two cold chain scenarios: Polyethylene was used as wall insulation for CA storage in one chain, while Vacuum Insulation Panel (VIP) was used in the other chain.

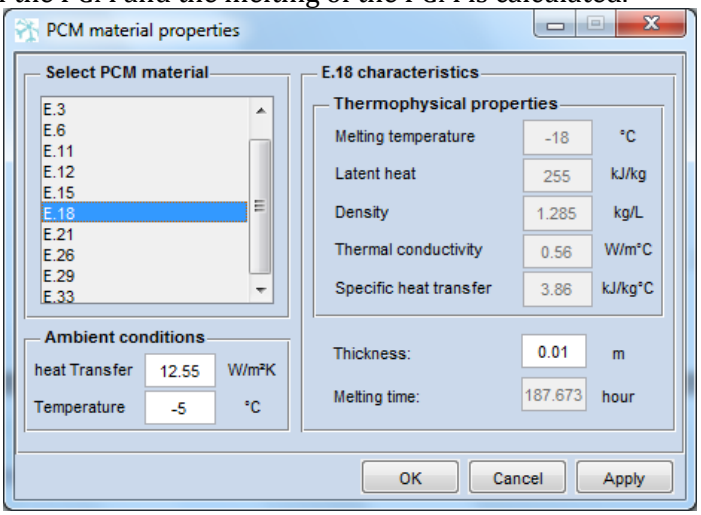
Phase Change Materials (PCMs) covers

Phase Change Materials (PCM)

Users can down simulate the use of PCM covers in cold rooms by selecting the checkbox "Use PCM cover around product" in the properties window. The PCM types and properties can be modified by clicking on "Edit PCM".



The window PCM material properties opens. Different PCM can be selected. In addition, the thermophysical properties of the selected PCM is displayed, but cannot be modified. Users can specify the thickness of the PCM and the melting of the PCM is calculated.

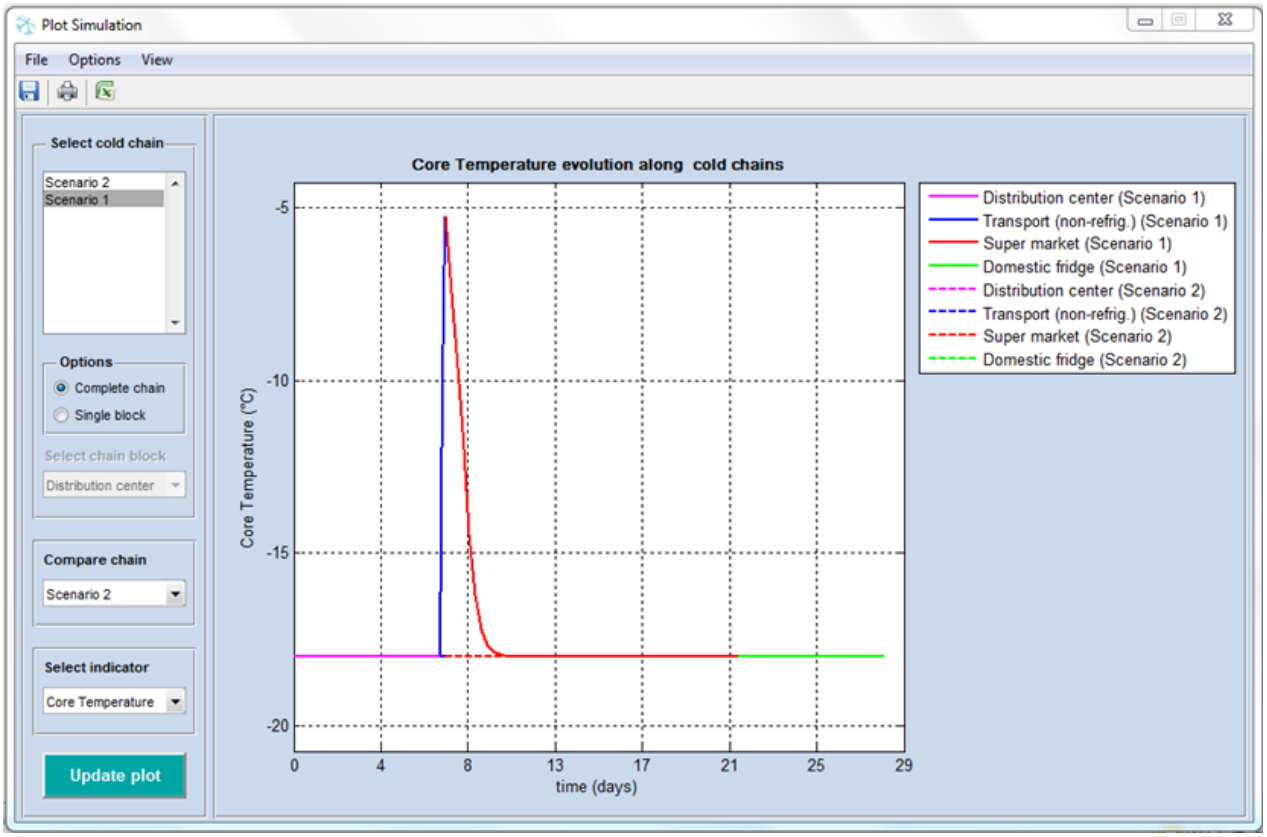


The product temperature can be simulated based on the melting time and the melting temperature of the selected PCM.

Example: Consider the following two cold chain scenarios

Cold chain blocks	Scenario 1			Scenario 2		
	Set T	Duration	PCM cover	Set T	Duration	PCM cover
Distribution storage	-18 °C	7 d	None	-18 °C	7 d	None
Non-refrigerated transport	15 °C	6 h	None	15 °C	6 h	E.18
Display cabinet	-18 °C	14 d	None	-18 °C	14 d	None
Domestic fridge	-18 °C	7 d	None	-18 °C	7 d	None

The resulting effect of using the PCM cover can be seen in the figure below:



Graphical output from FRISBEE tool chain simulations during two cold chain scenarios: No PCM was used for distribution storage of ice cream at -15°C for 7 days in one chain, while PCM cover was used in the other chain for same storage temperature and duration.

Monte Carlo Simulations

The Monte Carlo option was not implemented for all food products and for all quality models. Table 2 presents the products and quality models available for the Monte Carlo simulation

Safety and Quality Indicators for the selected food

Category	Food product	Safety Indicator	Quality Indicator
Meat	Pasteurized ham	*Listeria monocytogenes*	
Fruit	Apple		firmness, colour
Milk products	Ice cream	-	texture, colour, sensory attribute, ice crystal size
Vegetables	Spinach	-	vitamin C, colour, texture

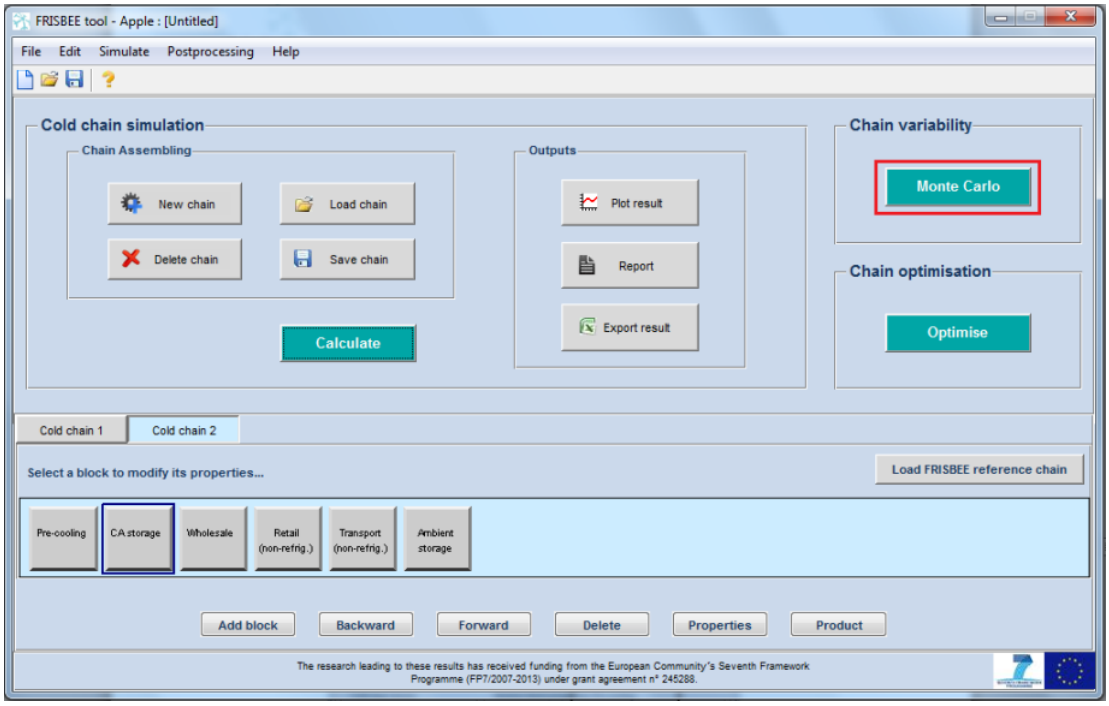
Cold chain blocks: Some equipment are not available in the Monte Carlo simulation. Table 2 presents the available links.

Cold chain links in Monte Carlo simulation

Product	**Apple chilled chain**	**Pasteurized cooked ham**	**Spinach & Ice cream**
Links	Pre-cooling	Chilled storage	Frozen storage
	CA storage	Refrigerated transport	Refrigerated transport
	Refrigerated transport	Expedition storage	Distribution center
	Wholesale	Display Cabinet	Super market
	Non-refr transport	Non-refr transport	Domestic fridge
	Domestic fridge	Domestic fridge	

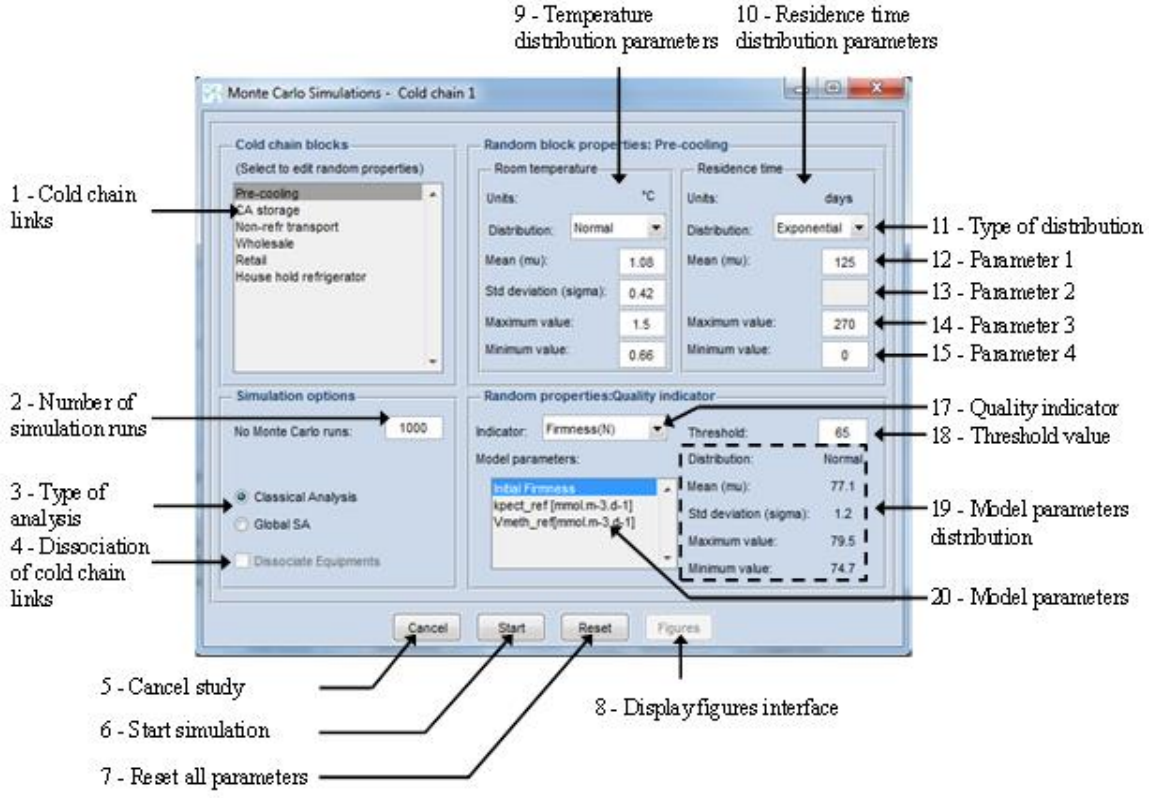
Running Monte Carlo simulations

Click on Monte Carlo to open Monte Carlo Simulation window for the selected cold chain.



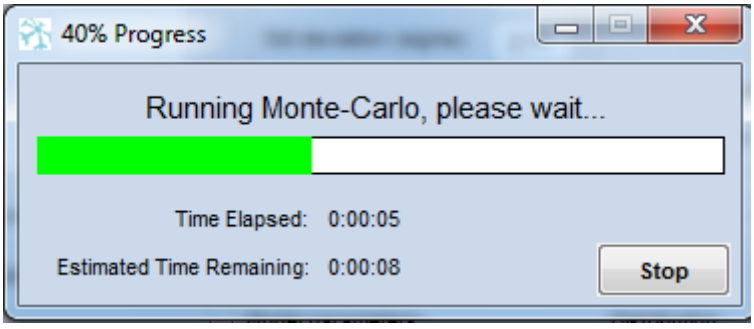
Monte Carlo simulation window

Select a link to modify its temperature and residence time distribution.



Classical Analysis (Accept and reject algorithm)

The simulation is performed from the first to the last equipment for 2000 food products (Note: the number of simulation runs can be changed, “number of simulation runs” **(2)**).
Food products of which final quality respects the quality criterion are “accepted”.
Food products of which final quality do not respect the quality criterion are “rejected”.
To run a simulation, click on the radio button “classical analysis” **(3)** and then click on the start button **(6)**. Only the evolution of the selected quality model **(17)** is calculated.



Monte Carlo simulation plots

The window “Monte Carlo results” is opened automatically after the calculation. The histograms of the initial and final product quality are displayed.

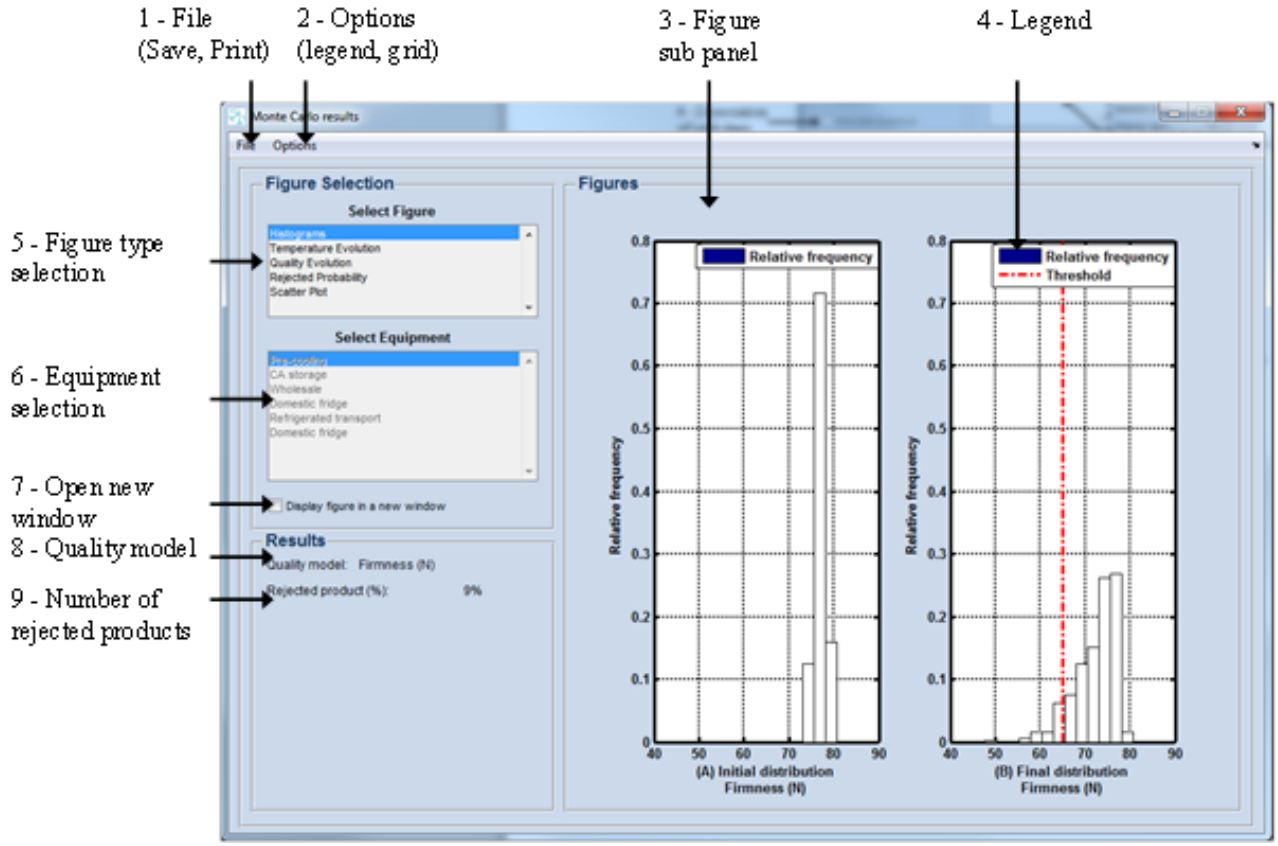


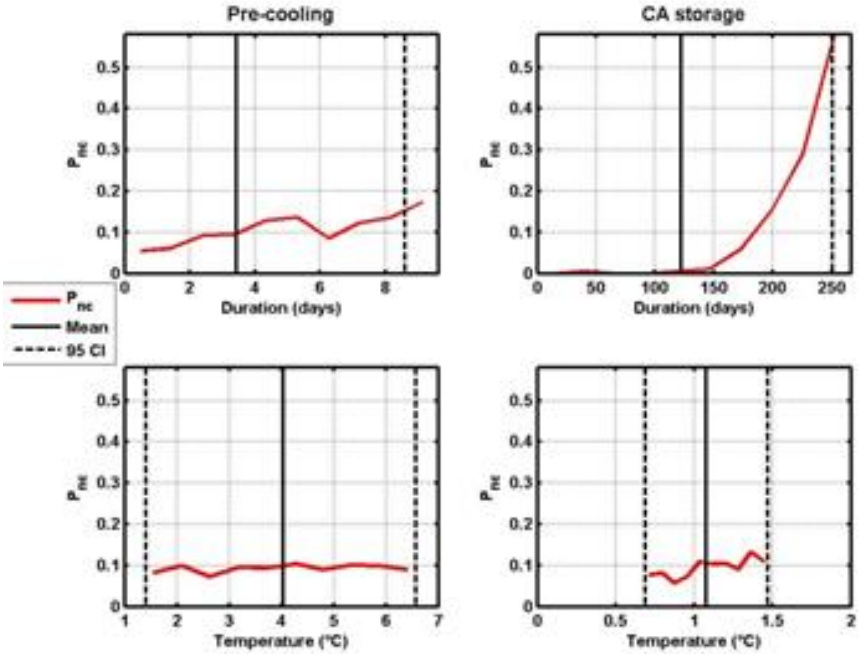
Figure type

5 different figures can be selected (5) (histograms, Temperature evolution, Quality evolution, Rejected Probability, Scatter plots). The figure can be opened in a new window by clicking on the checkbox “Display figure in a new window” (7).

a) Rejected probability

The rejected probability shows the proportion of products of which final quality (at the end of the chain) do not respect the quality criteria along the range of the temperature or the duration in the cold chain link.

Example (firmness of apple): The CA storage, all products stored during 50 days were accepted (P_{nc} =0) while 15% of products stored during 200 days do not respect the quality criteria at the end of the cold chain (Sub figure top-right). It shows the impact of the duration in the CA storage. On the contrary, the temperature in the precooling step (sub figure bottom left) had no impact because the probability of non-compliance is constant (10%) in the range of variation of this input.

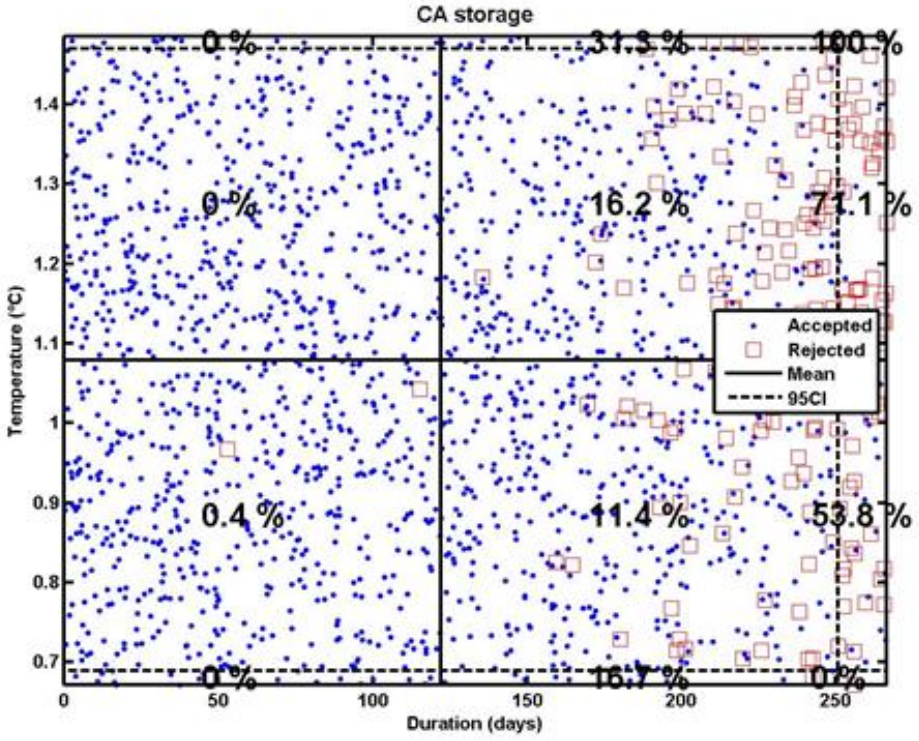


b) Scatter plot

The scatter plot shows the interaction between the temperature and the duration in a link. Blue points are the accepted products (of which the quality at the end of the chain respects the quality criteria) and the red square are the rejected products (of which the quality at the end of the chain does not respect the quality criteria), the percentage represents the proportion of rejected products.

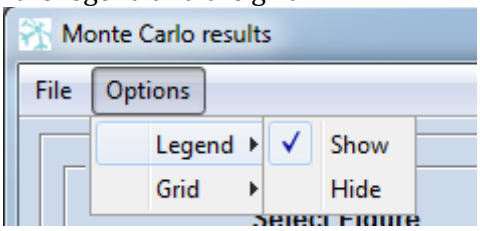
Example (firmness of apples in CA storage):

0% of product stored below the mean duration are rejected, 11.4 % of products stored below the between 1.1°C and 0.7°C and 120 and 250 days are rejected. 16.4 % of products stored between 1.1°C and 1.45°C and between 120 and 250 days are rejected are rejected.



Show/hide legend and grid

Click on options to hide or show the legend and the grid.

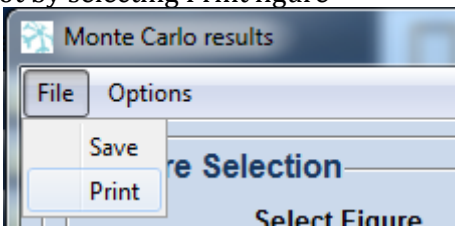


Save plot figure

The figure can be saved as an image file (png, tiff, jpg, Matlab fig)

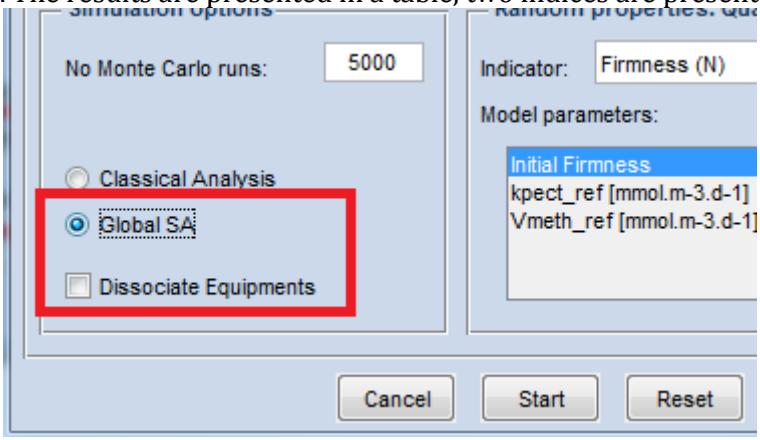
Print figure

Send a print command for the plot by selecting Print figure



Global Sensitivity analysis

To run the global sensitivity analysis, click on the radio button "Global SA" (**3** on the Monte Carlo simulation window). The results are presented in a table, two indices are presented.

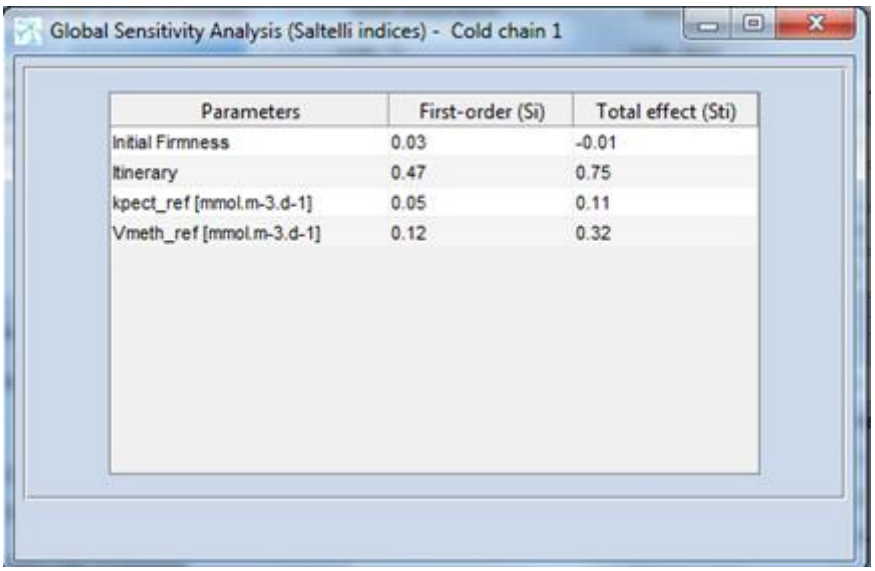


- S_i (First order index): This index represents the impact of the parameter on the product final quality without the interaction with the other parameters. The value of S*i* is included between 0 and 1. If S_i is closed to 0, the parameter has no impact on the final quality, if S_i is closed to 1; the parameter has a great impact on the product final quality.

- S_{ti} (Total effect index): This index represents the impact of the parameter on the final quality of the products with the interactions with the other parameters. If $S_{ti} < 0.1$ the parameter has no impact of the final quality, if $S_{ti} > 0.1$ the parameter is signicant.

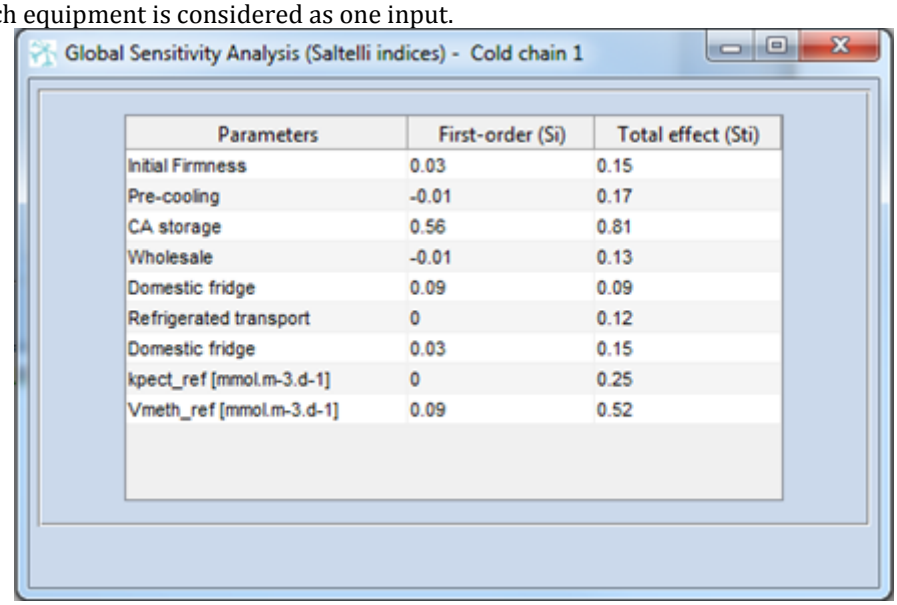
Two options are possible:

a) All equipment are considered as one parameter called “Itinerary”
This solution should be chosen first. If the itinerary has a great impact as in the table below, the option can be simulate to identify which link has the greatest impact.



Parameters	First-order (Si)	Total effect (Sti)
Initial Firmness	0.03	-0.01
Itinerary	0.47	0.75
kpect_ref [mmol.m-3.d-1]	0.05	0.11
Vmeth_ref [mmol.m-3.d-1]	0.12	0.32

b) Each equipment is considered as one input.



Parameters	First-order (Si)	Total effect (Sti)
Initial Firmness	0.03	0.15
Pre-cooling	-0.01	0.17
CA storage	0.56	0.81
Wholesale	-0.01	0.13
Domestic fridge	0.09	0.09
Refrigerated transport	0	0.12
Domestic fridge	0.03	0.15
kpect_ref [mmol.m-3.d-1]	0	0.25
Vmeth_ref [mmol.m-3.d-1]	0.09	0.52

Multi-objective optimisation

Implementation in the QEEAT

The multi-objective optimization has been implemented in the FRISBEE tool. The Global optimization tool box of the Matlab was used. Therefore, except for the compiled version, the multi-objective optimization of the FRISBEE tool can only run if the user has the global optimization tool box installed in his/her Matlab.

Running multi-objective optimisation

- The following steps are involved in running the multi-objective optimisation algorithm .
- After building a cold chain, and modifying properties to desired set points, the multi-objective optimisation can be run by clicking the "Optimise" button from the Chain optimisation panel
-

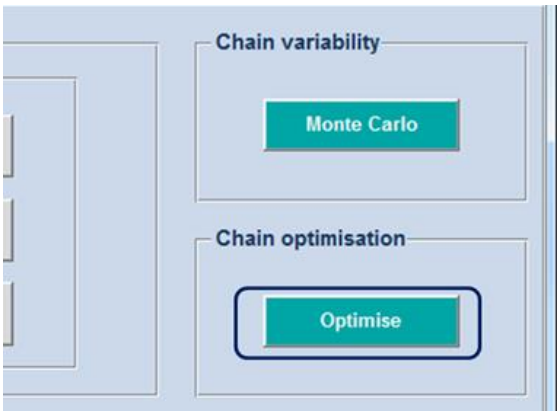


Fig. 1. The Main window of the FRISBEE tool. User can begin multi-objective optimisation by clicking on "Optimise"

The following window opens.

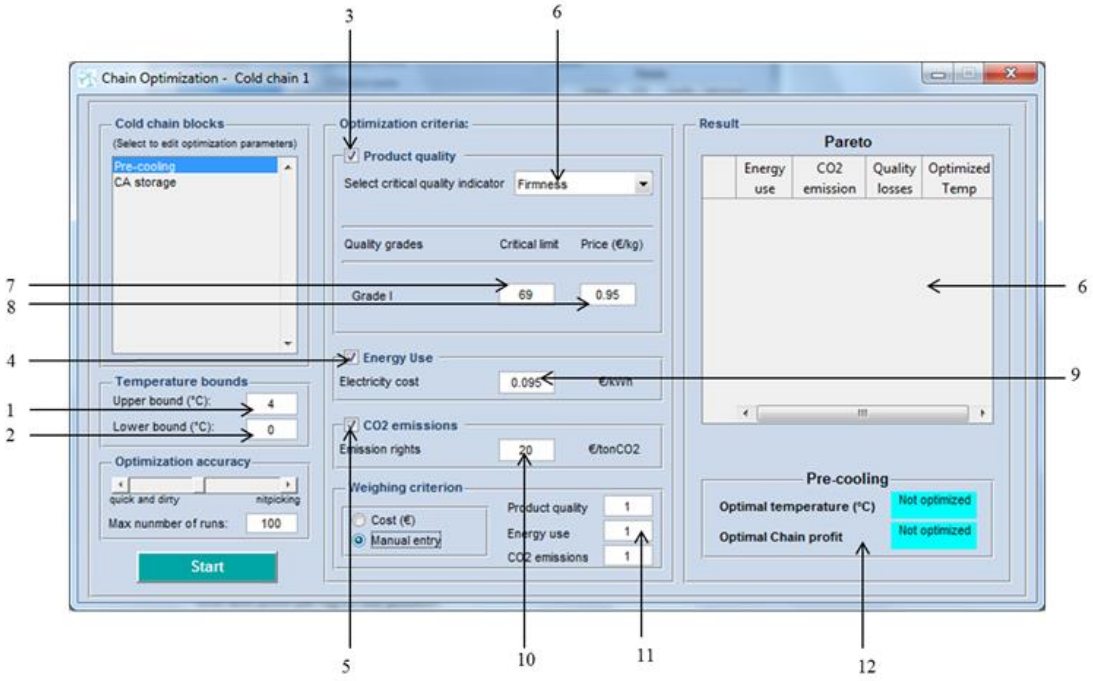


Fig. 2. Chain optimisation window

- From the chain optimisation window, a user can select one or more objective functions by selecting the checkboxes for "Product quality" (3), "Energy use" (4) and "CO_2 emissions" (5).
  - The temperature bounds are specified by entering an upper and a lower temperature bound (1 and 2). Default values are provided.
  - If product quality is selected as an optimization criterion, the user needs to specify which quality indicator should be considered as the critical indicator for quality (6), and the critical limit (7) and price per kg of the product (8).
  - If energy use is selected as an optimization criterion, the user needs to specify the cost of electricity (9).
  - If a CO_2 emission is selected as an optimization criterion, the user needs to specify the cost of the emission right of one ton of CO_2 (10).
  - Additionally, a user can chose to manually enter the weights of each objective function in case he/she does not want to use the weighted multi-objective function (11). In this case, he/she must select the radio button "Manual entry" and the option will be provided to enter weights (11)

- Once all these have been specified for each cold chain block, the user can begin the optimisation by clicking on the "Start" button. The follwoing windows pop opens, and display the progress of the optimisation

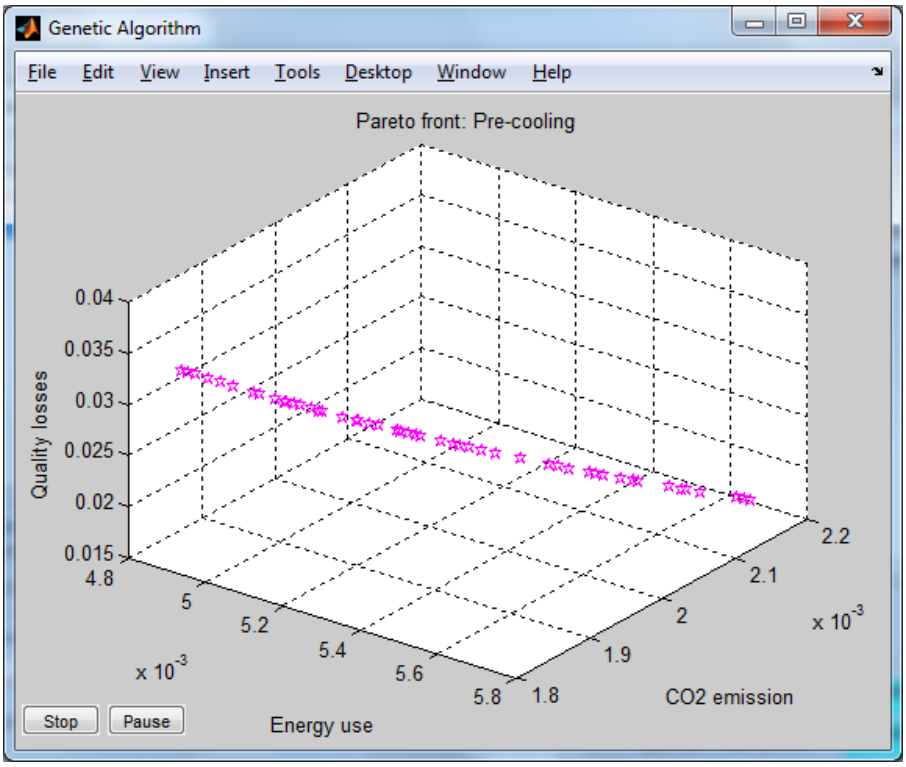


Fig 3. Progress of optimisation

- The user may click on the "stop" button to manually terminate the optimisation.

After optimisation, the pareto solution, together with the optimised temperature is displayed in a table in the chain Optimisation window (Fig. 4).

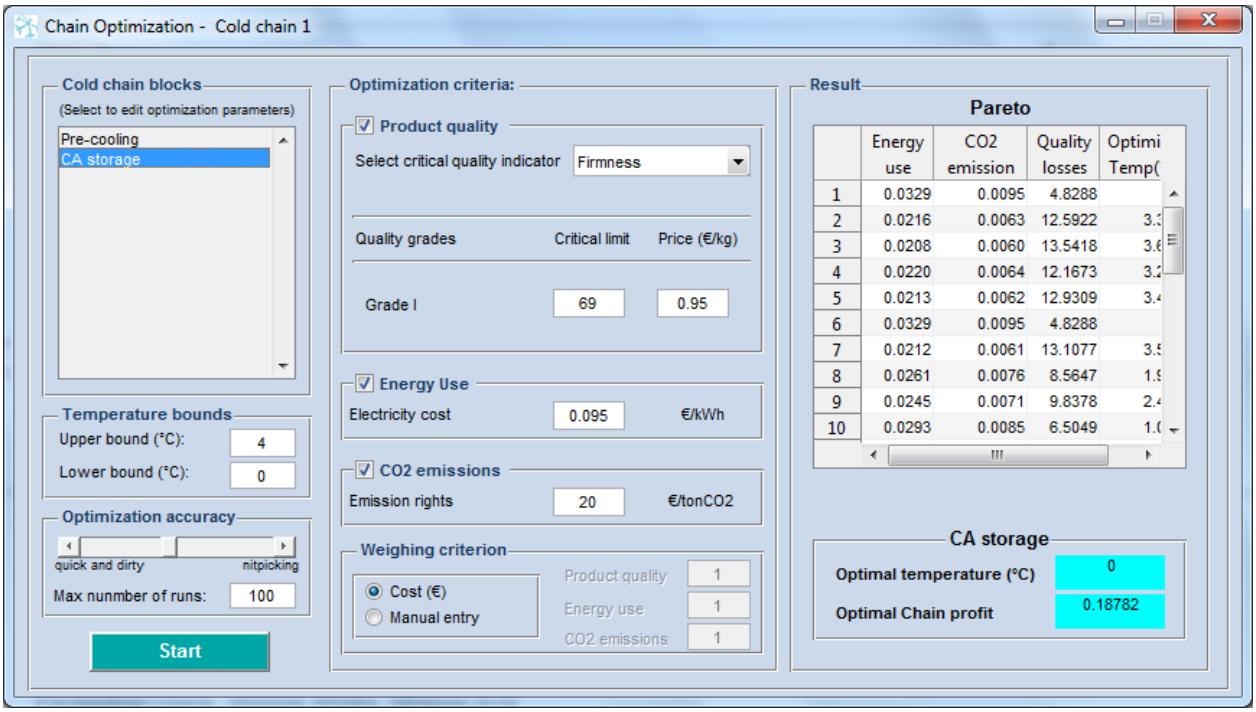


Fig. 4. Example of chain optimisation: apple cold chain.

- Both the optimal (maximum) chain profit and the corresponding temperature is shown in Fig. 4.

NB:

- The multi-objective optimisation works only for refrigerated blocks, since in the FRISBEE Tool we calculate energy and CO2 emission by refrigeration equipment.

Reference information

In this section, some background information about the FRISBEE Tool is provided. These include:

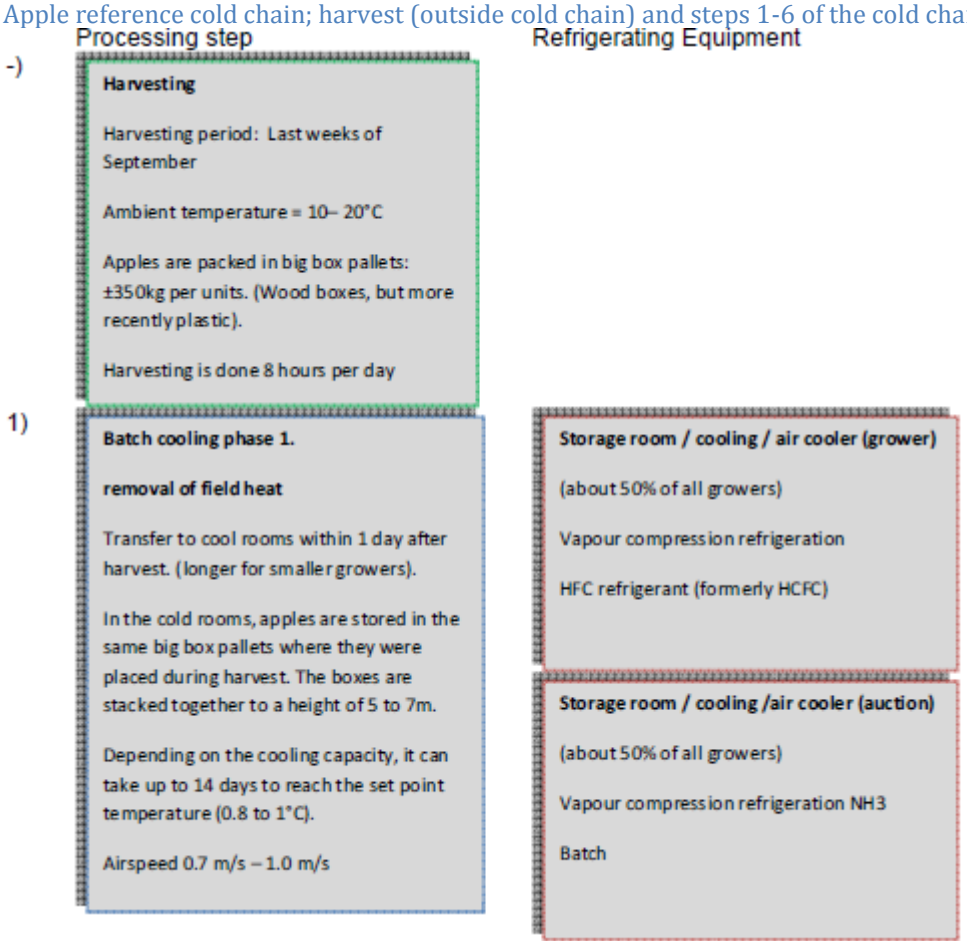
- Definition of the FRISBEE referenece cold chain
- Kinetic models for different quality indicators
- Heat loads and energy calculations
- Global warming impact assessment
- Superchilling and supercooling
- Phase Change Materials (PCM)
- Multi-objective optimisation

Reference cold chains

Apple cold chain

The apple cold chain plays a role in one of the innovative technologies that are under study in the Frisbee project: Dynamic Controlled Atmosphere storage. It is therefore necessary to define a reference cold chain for apple storage, with which the innovative technology can be compared in terms of Quality, Energy consumption and environmental impact.

Apple reference cold chain; harvest (outside cold chain) and steps 1-6 of the cold chain


Processing step
Refrigerating Equipment
-)
Harvesting
Harvesting period: Last weeks of September
Ambient temperature = 10– 20°C
Apples are packed in big box pallets: ±350kg per units. (Wood boxes, but more recently plastic).
Harvesting is done 8 hours per day
1)
Batch cooling phase 1.
removal of field heat
Transfer to cool rooms within 1 day after harvest. (longer for smaller growers).
In the cold rooms, apples are stored in the same big box pallets where they were placed during harvest. The boxes are stacked together to a height of 5 to 7m.
Depending on the cooling capacity, it can take up to 14 days to reach the set point temperature (0.8 to 1°C).
Airspeed 0.7 m/s – 1.0 m/s
Storage room / cooling / air cooler (grower)
(about 50% of all growers)
Vapour compression refrigeration
HFC refrigerant (formerly HCFC)
Storage room / cooling /air cooler (auction)
(about 50% of all growers)
Vapour compression refrigeration NH3
Batch

2)

Batch cooling phase 2.

controlled atmosphere

Once the set point temperature is reached, the gas composition of the room is modified (CA).

Storage temperature +0.8 - +1°C

Gas composition 1% O_2 and 2.5 - 3.0% CO_2.

Duration: up to 9 months

Oxygen scrubber

Active carbon to remove O_2 , replace with N_2

Carbon dioxide (CO_2) scrubber

Removes excess CO_2 produced by respiration using active carbon.

-)

International Transport
(not considered as reference)

Near: 4-5 days, by refrigerated trucks.

Air 10°C, normal atmosphere.

Distant: up to 30 days, refrigerated ships

Air 1°C, controlled atmosphere

3)

Road Transport (National, reference)

Normal air, ambient temperature.

Duration is usually a few hours.

Road transport – not conditioned

Ambient temperature depending on outdoor conditions.

4)

Whole sales (in Belgium)

Whole sellers buy apples from auctions or from growers who store apples themselves.

Growers might choose to bring out apples when prices are high.

Whole sellers temporally store apples (together with other fruits) at 10 to 15°C in normal atmosphere.

Some are packaged in small packs of 4 or 6 apples. Others are sold without packaging, in pallet boxes of 10 to 12 kg.

Cooling cell at wholesale

Compression refrigeration NH_3 (or HFC)

Packing material: Cardboard trays, polystyrene trays, polyethylene film.

5)

Transport (reference)

Transport by trucks from wholesaler to supermarkets and retail stores: Normal air, ambient temperature. Duration is usually a few hours.

Road transport – not conditioned

Ambient temperature depending on outdoor conditions.

6)

Retails (in Belgium)

No cooling, normal atmosphere (r)

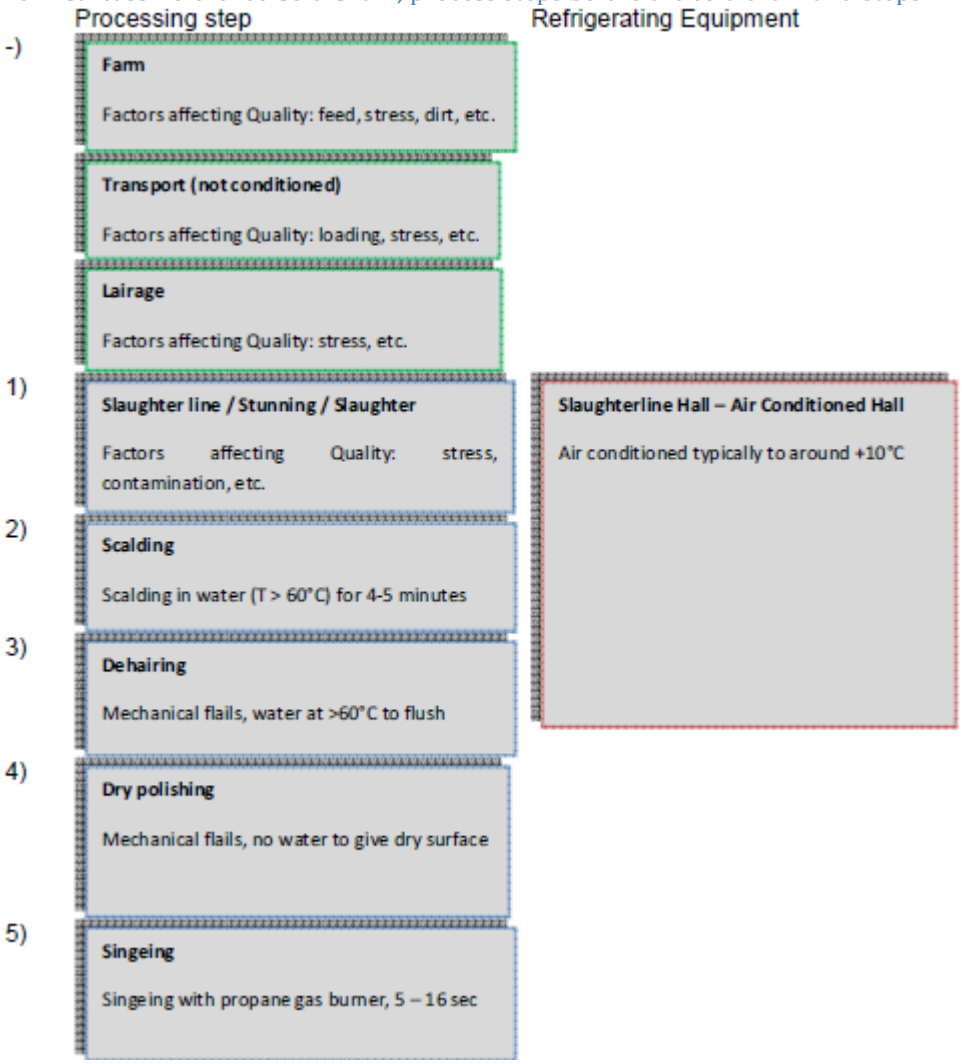
Retail apple cooling (not reference)

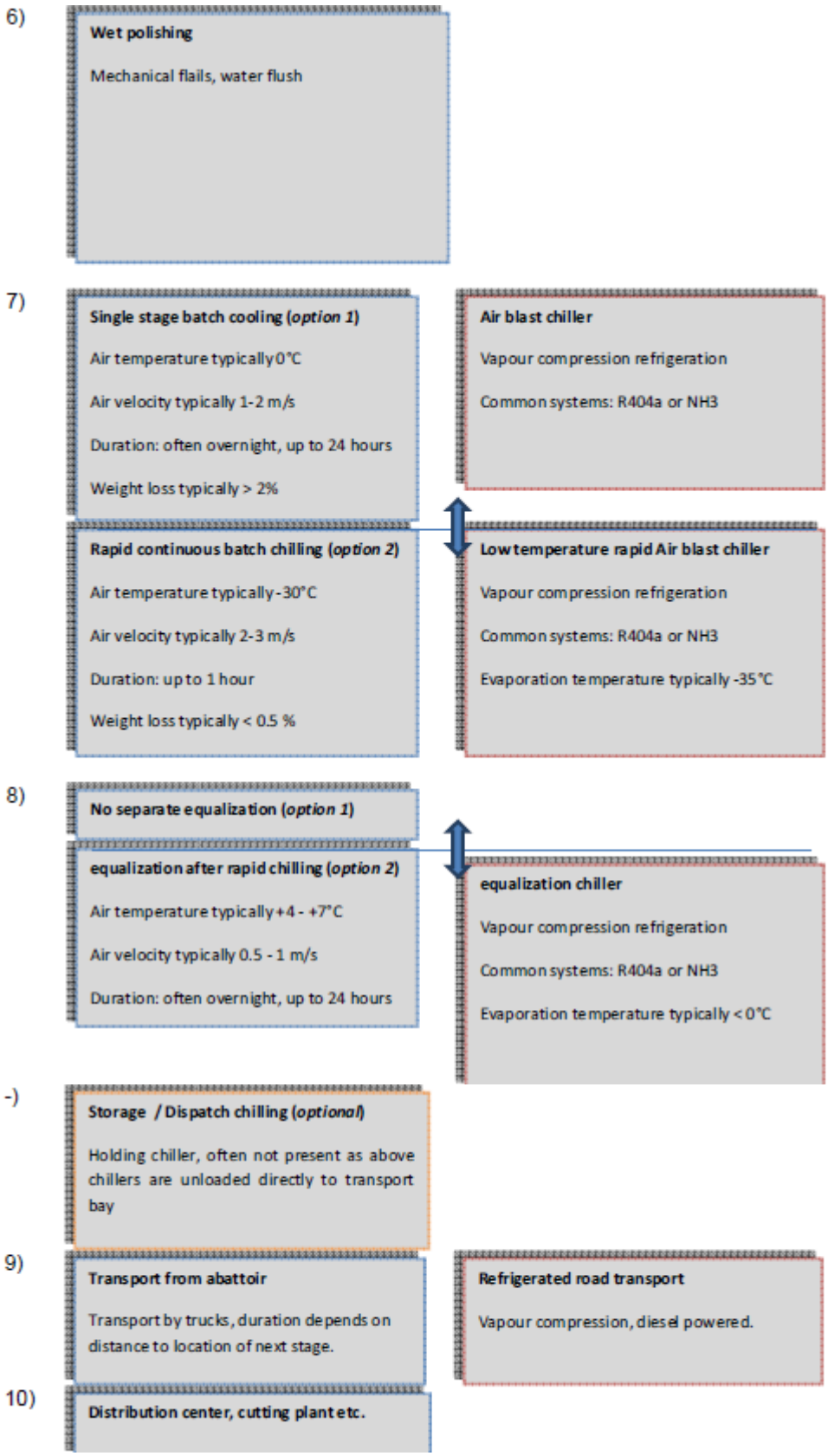
The Belgian Colruyt supermarket stores apples at 12°C in a walk-in cooler

Pork carcass cold chain

The pork carcass cold chain features in innovative technologies for fast chilling of meat products, such as vascular perfusion chilling. The chain is depicted in
the figure below. The first three stages indicated below do not belong to the cold chain – as they are not temperature conditioned – but these stages do include
factors that affect initial quality, such as microbiology, texture, temperature etc.

Pork Carcass Reference Cold Chain; process steps before the cold chain and steps 1-10 of the cold chain



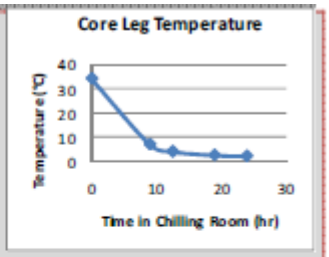

6)
Wet polishing
Mechanical flails, water flush
7)
Single stage batch cooling (option 1)
Air temperature typically 0°C
Air velocity typically 1-2 m/s
Duration: often overnight, up to 24 hours
Weight loss typically > 2%
Air blast chiller
Vapour compression refrigeration
Common systems: R404a or NH3
Rapid continuous batch chilling (option 2)
Air temperature typically -30°C
Air velocity typically 2-3 m/s
Duration: up to 1 hour
Weight loss typically < 0.5 %
Low temperature rapid Air blast chiller
Vapour compression refrigeration
Common systems: R404a or NH3
Evaporation temperature typically -35°C
8)
No separate equalization (option 1)
equalization after rapid chilling (option 2)
Air temperature typically +4 - +7°C
Air velocity typically 0.5 - 1 m/s
Duration: often overnight, up to 24 hours
equalization chiller
Vapour compression refrigeration
Common systems: R404a or NH3
Evaporation temperature typically < 0°C
-)
Storage / Dispatch chilling (optional)
Holding chiller, often not present as above chillers are unloaded directly to transport bay
9)
Transport from abattoir
Transport by trucks, duration depends on distance to location of next stage.
Refrigerated road transport
Vapour compression, diesel powered.
10)
Distribution center, cutting plant etc.

Sliced pork meat cold chain

Non frozen sliced pork meat

Sliced pork meat is a “candidate” for the super chilling process, which has so far been mostly applied to fish (salmon). The first part of the cold chain, before
cutting, is identical to the pork carcass cold chain, described in paragraph 3.2. In this paragraph, the process before the rapid continuous batch chilling process is assumed the same as that described for the pork carcass, and the further process starts with the rapid continuous batch chilling process (option 2), at an air temperature of -20°C (i.e. not equal to the typ ical temperature of -30°C as mentioned in 3.2).

Sliced pork meat Reference Cold Chain, non frozen.

	Process steps	Refrigerating Equipment
1-6)	**Process steps as in Pork Carcass cold chain from start to wet polishing (steps 1-6). For a complete description refer to paragraph 2.2**	**Slaughterline Hall – Air Conditioned Hall** Air conditioned typically to around +10°C
7)	**Shock Freezer** **Rapid continuous batch chilling (*option 2*)** Air temperature -20°C Air velocity typically 1-2 m/s Duration: 70 minutes Core temp. leg +40.0 °C in / 34.5 °C out Surface temp. +40.0 °C in / -20.0 °C out (temperatures ± 0.5 °C at prod. mass 75 kg)	 **Low temperature rapid Air blast chiller** Vapour compression refrigeration, 2-stage Common systems: R404a or NH3 Evaporator temp shock freezer: -26°C Evaporator temp chilling room: -3°C Evaporator temp processing room: +5°C Evaporator temp chilled storage: -3°C Evaporator temp expedition storage: -3°C
8)	**Equalization (chilling room)** Air temperature +1.7°C Air velocity 0.5 - 1 m/s Duration 24 hours Core temp. leg +34.5 °C in / 2.1 °C out Surface temp. -20.0 °C in / 1.7 °C out (temperatures ± 0.5 °C at prod. mass 75 kg)	

9)

Processing room; cutting and packaging

Air temperature +10 °C

Air velocity 0.1 – 0.5 m/s

Duration typically 60 minutes

The carcasses are parted, and different parts follow different processing.

Pork neck is cut into cutlet and packed into consumer packing, Unit weight 0.5 kg, and further in paper cartoons and put on pallets

Temperature neck in: 2.1 °C, Out 3.0 °C

Duration approximately 60 min

Pork neck unit weight: 3 kg, L=30cm (+/- 3 cm), Ø=15 cm (+/- 2 cm)

Packing material:
A-PET containers (Polyethylene terephthalate), top sealed.
Modified atmosphere (60/40 CO_2/N_2)

Measure outside: 200x135x60 mm
Thickness: 3 mm; headspace: 1 cm
Thermal conductivity: 0.15-0.24 W/m.K.
Specific heat: 1900 J/kg.K
Density: 1037 kg/m^3

10)

Chilled product storage room

Air temperature +2 °C

Air velocity 0.5 - 1 m/s

Duration average 48 hours

Neck cutlet temperature +3 °C in / 2 °C out

Low temperature rapid Air blast chiller

Vapour compression refrigeration, 2-stage

Common systems: R404a or NH3

Evaporator temp shock freezer: -26°C
Evaporator temp chilling room: -4°C
Evaporator temp processing room: +5°C
Evaporator temp chilled storage: -6°C
Evaporator temp expedition storage: -6°C

11)

Expedition storage

Air temperature +2 °C

Air velocity 0.5 - 1 m/s

Duration average 12 hours

Neck cutlet temperature +2 °C in / +2 °C out

12)

Refrigerated Road Transport

Haugesund (N) to Oslo (455 km)

Air temperature +2 °C

Air velocity:

Duration average 6 hours

Neck cutlet temperature +2 °C in / 2 °C out

Refrigerated road transport

Vapour compression, diesel powered.

13)

Distribution Center (Oslo)

Air temperature +2 °C

Air velocity:

Duration average 12 hours

Neck cutlet temperature +2 °C in / 2 °C out

Industrial Refrigeration System

Vapour compression refrigeration NH3

- Capacity for chilling (Air at +2°C)
- Capacity for freezing (Air at -18 °C)

14)

Refrigerated Road Transport

Oslo to supermarkets in Oslo region

Air temperature +2 °C

Refrigerated road transport

Vapour compression, diesel powered.

15)

Supermarket

Oslo region

Air temperature +4 °C

Air velocity:

Duration average 96 hours (4 days)

Neck cutlet temperature +2 °C in / 4 °C out

Supermarket Refrigeration system

Vapour compression refrigeration, DX

Supermarket Refrigerated Storage

Vapour compression refrigeration

Air temperature +4 °C

Supermarket Refrigerated Display Case

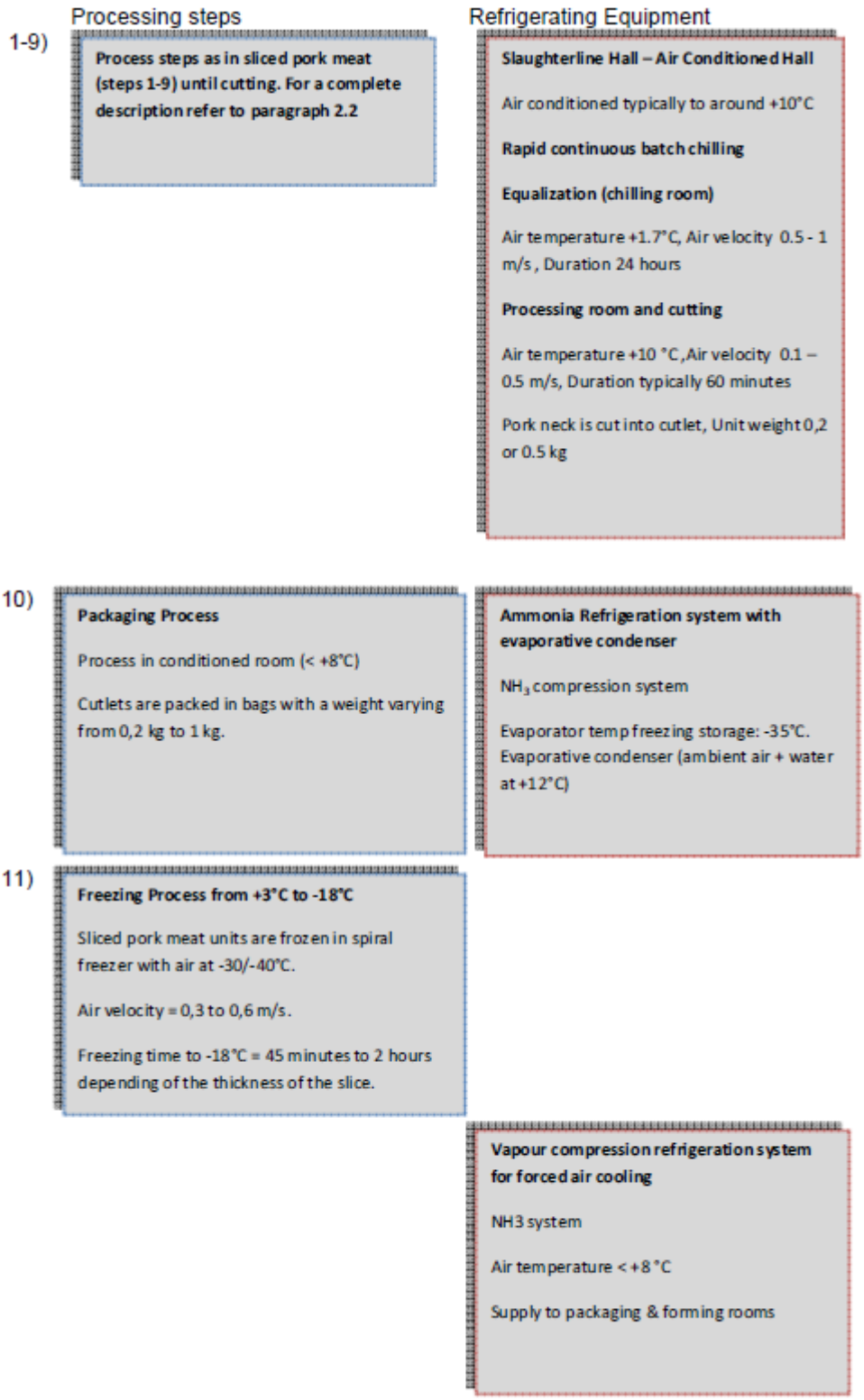
Vapour compression refrigeration

Air temperature +4 °C

Frozen sliced pork meat

The first part of the cold chain, before packaging, is identical to the sliced pork meat, described in paragraph 3.2. In this paragraph, the process before the freezing process is assumed the same as that described for the sliced pork meat, and the further process starts with the rapid freezing IQF process at an air temperature of -30/-40°C.

Sliced pork meat Reference Cold Chain, frozen.


Processing steps
Refrigerating Equipment
1-9)
Process steps as in sliced pork meat (steps 1-9) until cutting. For a complete description refer to paragraph 2.2
Slaughterline Hall – Air Conditioned Hall
Air conditioned typically to around +10°C
Rapid continuous batch chilling
Equalization (chilling room)
Air temperature +1.7°C, Air velocity 0.5 - 1 m/s , Duration 24 hours
Processing room and cutting
Air temperature +10 °C ,Air velocity 0.1 – 0.5 m/s, Duration typically 60 minutes
Pork neck is cut into cutlet, Unit weight 0,2 or 0.5 kg
10)
Packaging Process
Process in conditioned room (< +8°C)
Cutlets are packed in bags with a weight varying from 0,2 kg to 1 kg.
Ammonia Refrigeration system with evaporative condenser
NH3 compression system
Evaporator temp freezing storage: -35°C. Evaporative condenser (ambient air + water at +12°C)
11)
Freezing Process from +3°C to -18°C
Sliced pork meat units are frozen in spiral freezer with air at -30/-40°C.
Air velocity = 0,3 to 0,6 m/s.
Freezing time to -18°C = 45 minutes to 2 hours depending of the thickness of the slice.
Vapour compression refrigeration system for forced air cooling
NH3 system
Air temperature < +8 °C
Supply to packaging & forming rooms

12)

Cold Storage

Storage in cold store (-18/-22 °C)

Storage duration: some days to one year.

Ammonia Refrigeration system with evaporative condenser

NH_3 compression system

Evaporator temp freezing storage: -35°C. Evaporative condenser (ambient air + water at +12°C)

13)

Refrigerated Road Transport

Air temperature -18 °C

Refrigerated road transport (frozen)

Vapour compression refrigeration

Diesel powered

14)

Distribution Center

Air temperature -21 °C

Duration:

15)

Refrigerated Road Transport

Air temperature -18 °C

Industrial Refrigeration System

Vapour compression refrigeration NH3

- Capacity for chilling (Air at +2°C)
- Capacity for freezing (Air -18 °C)

Refrigerated road transport (frozen)

Vapour compression refrigeration

Diesel powered

16)

Supermarket (or restaurant)

Glass door or island freezer, -18°C

Supermarket DX refrigeration system

Description in section 0

Commercial island freezer -18°C

17)

Transport (not refrigerated)

18)

Household storage

Freezer, storage at -18°C

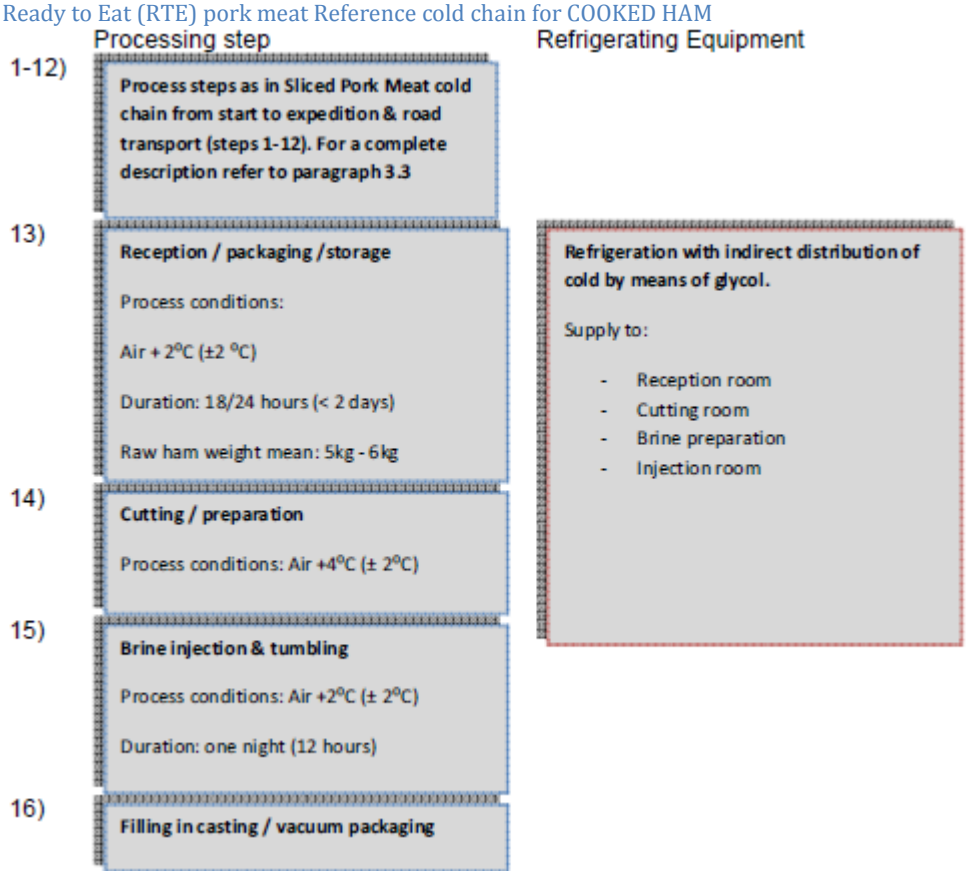
Household freezer -18°C

Vapour compression refrigeration

Ready to eat pork meat cold chain

The first part of the cold chain for ready to eat pork meat, follows the cold chain for sliced pork meat products (section 3.3). Of course, in the sliced pork meat
products cold chain the attention is focused on the neck cutlet; whereas in this case the focus is on the ham.

Ready to Eat (RTE) pork meat Reference cold chain for COOKED HAM


Processing step
Refrigerating Equipment
1-12)
Process steps as in Sliced Pork Meat cold chain from start to expedition & road transport (steps 1-12). For a complete description refer to paragraph 3.3
13)
Reception / packaging /storage
Process conditions:
Air + 2°C (±2 °C)
Duration: 18/24 hours (< 2 days)
Raw ham weight mean: 5kg - 6kg
Refrigeration with indirect distribution of cold by means of glycol.
Supply to:
- Reception room
- Cutting room
- Brine preparation
- Injection room
14)
Cutting / preparation
Process conditions: Air +4°C (± 2°C)
15)
Brine injection & tumbling
Process conditions: Air +2°C (± 2°C)
Duration: one night (12 hours)
16)
Filling in casting / vacuum packaging

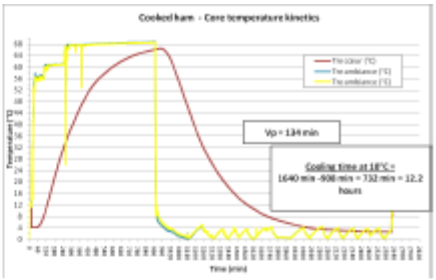
17) **Cooking**

Ambient temperature 56 - 68 °C

Duration: 15 hours

Ham weight 5-6 kg

Core temperature end: 66 °C



18) **Quick cooling**

Reduces core temperature to =10°C in less than 2 hours.

Conditions: Air 0°C - 1°C, high airspeed

HFC Refrigeration system (DX, cooling)

19) **Removal from casting**

Process conditions: Air +2°C (± 2°C)

Refrigeration with indirect distribution of cold by means of glycol.

Supply to:

- Process step 19)
- Cutting room
- Packaging room
- Storage room

20) **Cutting & slicing**

Process conditions: Air +2°C (± 2°C)

Duration: 30 min. – 1 hour

21) **Packaging** Modified atmosphere (50/50 CO_2/N_2; < 0.9% residual O2

Process conditions: Air +4°C (± 2°C)

Duration: 10 minutes

22) **Storage ready to eat products**

Process conditions: Air +2°C (± 2°C)

Duration: 3 hours – 1 night

23) **Expedition**

The reference cold chain for another ready to eat pork meat product, pate, generally follows the same process route as the cooked ham cold chain; and the process equipment for refrigeration is exactly the same.

Ready to eat pork products Reference cold chain: PATÉ

	Processing step	Refrigerating Equipment
1-12)	**Process steps as in Sliced Pork Meat cold chain from start to expedition & road transport (steps 1-12). For a complete description refer to paragraph 3.3**	
13)	**Reception / packaging /storage** Process conditions: Air + 2°C (±2 °C) Duration: 18/24 hours (< 2 days)	**Refrigeration with indirect distribution of cold by means of glycol.** Supply to: - Reception room - Cutting room - Preparation room
14)	**Cutting / preparation** Process conditions: Air +4°C (± 2°C) Duration: 30 minutes	
15)	**Brine/salting & scalding** Process conditions: Air +2°C (± 2°C) Duration:	
16)	**Mixing** Process conditions: Air +6°C (± 2°C) Duration:	
17)	**Preparation: mincing; grinding** Process conditions: Air +6°C (± 2°C) Duration:	

18) **Filling in casting / vacuum packaging**

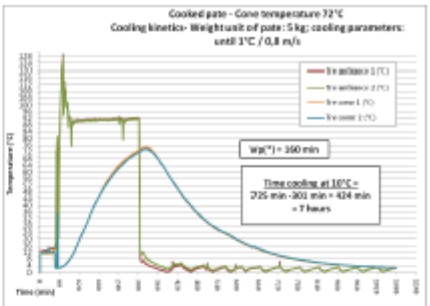
19) **Cooking**

Ambient temperature 128 - 92°C

Duration: 5 hours

Pate weight 5 kg

Core temperature end: 74 °C


Cooked pate - Core temperature 72°C
Cooling kinetics- Weight unit of pate : 5 kg; cooling parameters:
until 1°C / 0,8 m/s
Wp(°) = 360 min
Time cooling at 10°C =
225 min +201 min = 424 min
= 7 hours

20) **Quick cooling**

Reduces core temperature to ≈10°C in less than 2 hours.

Conditions: Air 0°C - 1°C, high airspeed

HFC Refrigeration system (DX, cooling)

21) **Removal from casting**

Process conditions: Air +2°C (± 2°C)

22) **Cutting & slicing**

Process conditions: Air +2°C (± 2°C)

Duration: 30 min. – 1 hour

23) **Packaging** Modified atmosphere (50/50 CO_2/N_2; < 0.9% residual O2

Process conditions: Air +4°C (± 2°C)

Duration: 10 minutes

24) **Storage ready to eat products**

Process conditions: Air +2°C (± 2°C)

Duration: 3 hours – 1 night

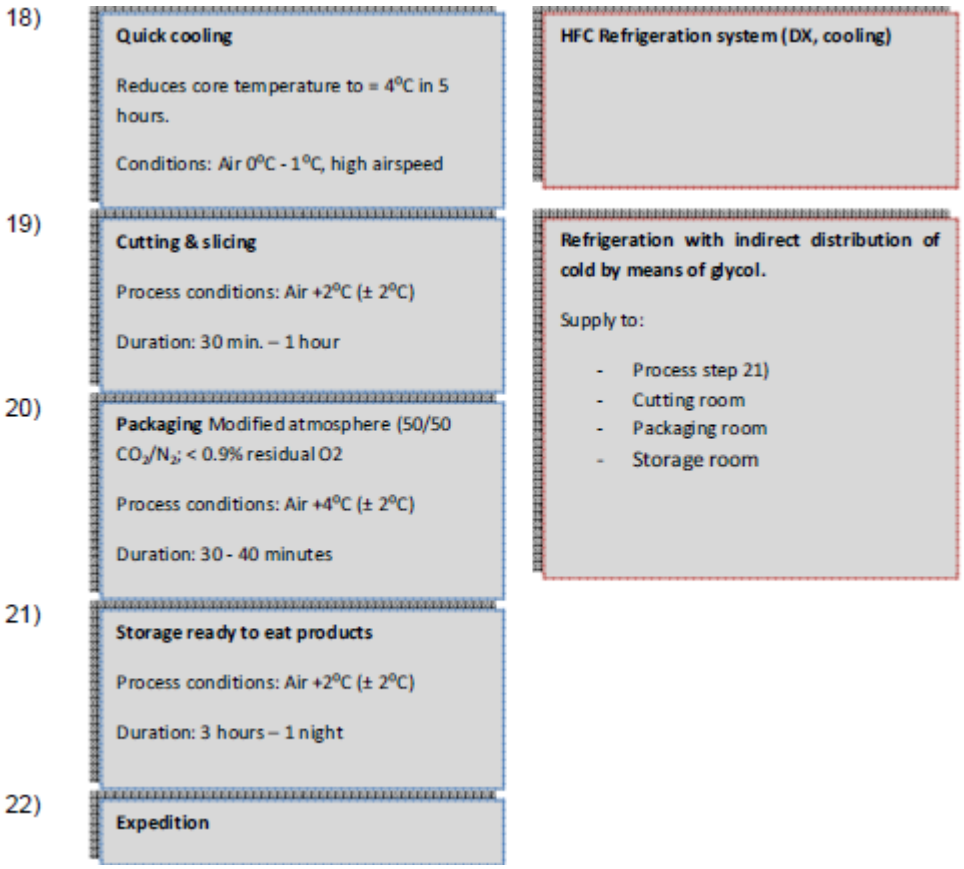
25) **Expedition**

Refrigeration with indirect distribution of cold by means of glycol.

Supply to:

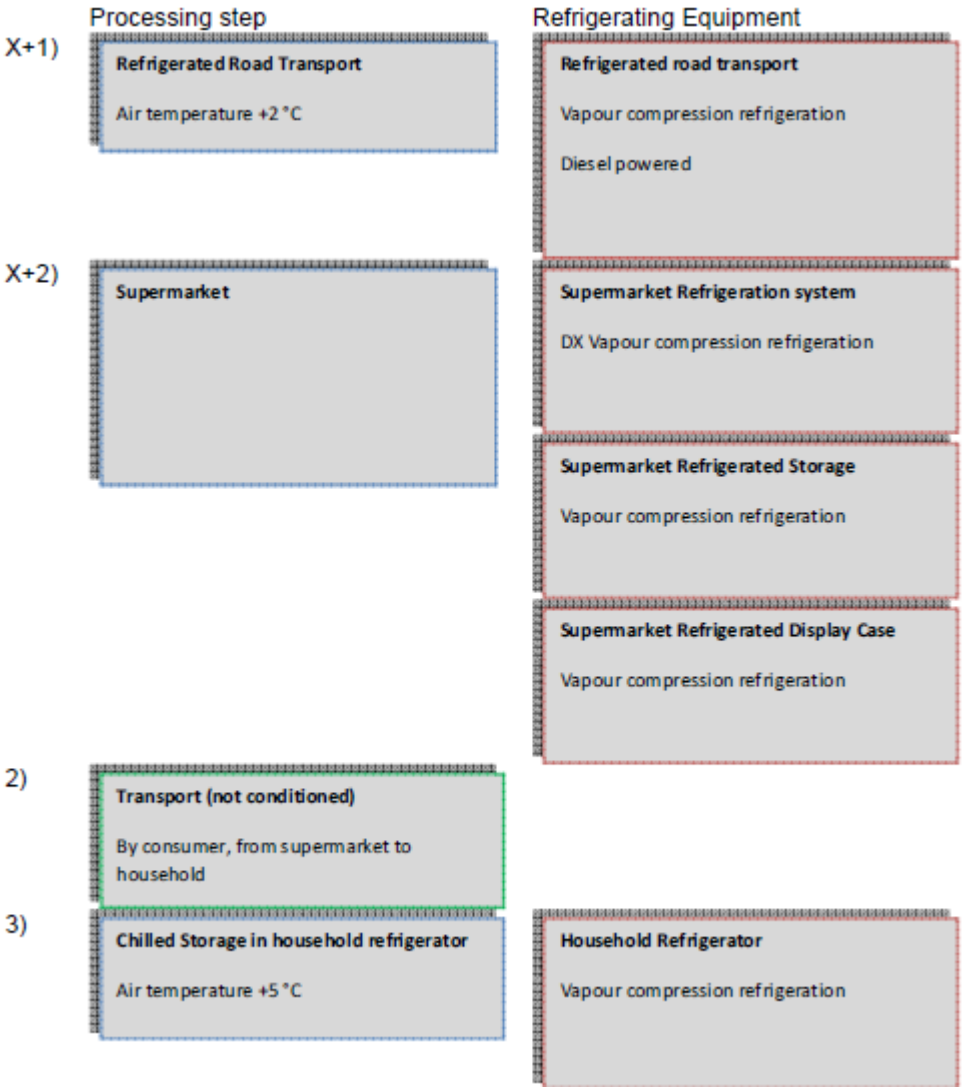
- Process step 21)
- Cutting room
- Packaging room
- Storage room

	Processing step	Refrigerating Equipment
1-12)	**Process steps as in Sliced Pork Meat cold chain from start to expedition & road transport (steps 1-12). For a complete description refer to paragraph 3.3**	
13)	**Reception / packaging /storage** Process conditions: Air + 2°C (±2 °C) Duration: 18/24 hours (< 2 days) Raw ham weight mean: 5kg - 6kg	**Refrigeration with indirect distribution of cold by means of glycol.** Supply to: - Reception room - Weighing section - Cutting room - Preparation room
14)	**Weighing** Process conditions: Air +4°C (± 2°C)	
15)	**Cutting / preparation** Process conditions: Air +4°C (± 2°C) Duration: 30 minutes	**Refrigeration with indirect distribution of cold by means of glycol.** Supply to: - Reception room - Weighing section - Cutting room - Preparation room
16)	**Brine injection & tumbling** Process conditions: Air +8°C (± 2°C) Duration: 18 hours	
17)	**Drying / Smoking cycles** Ambient temperature 45 - 50 °C Duration: 3-4 hours Ham weight ... kg Core temperature end: 30 °C	


18)
Quick cooling
Reduces core temperature to = 4°C in 5 hours.
Conditions: Air 0°C - 1°C, high airspeed
HFC Refrigeration system (DX, cooling)
19)
Cutting & slicing
Process conditions: Air +2°C (± 2°C)
Duration: 30 min. – 1 hour
Refrigeration with indirect distribution of cold by means of glycol.
Supply to:
- Process step 21)
- Cutting room
- Packaging room
- Storage room
20)
Packaging Modified atmosphere (50/50 CO_2/N_2; < 0.9% residual O2
Process conditions: Air +4°C (± 2°C)
Duration: 30 - 40 minutes
21)
Storage ready to eat products
Process conditions: Air +2°C (± 2°C)
Duration: 3 hours – 1 night
22)
Expedition

In the cold chains for “ready to eat pork meat” the last steps are “expedition”. From the expedition, the products are brought to the distribution center, or directly to the supermarket. The Reference cold chain steps for the second option (directly to the supermarket) are described in Table 40 below.

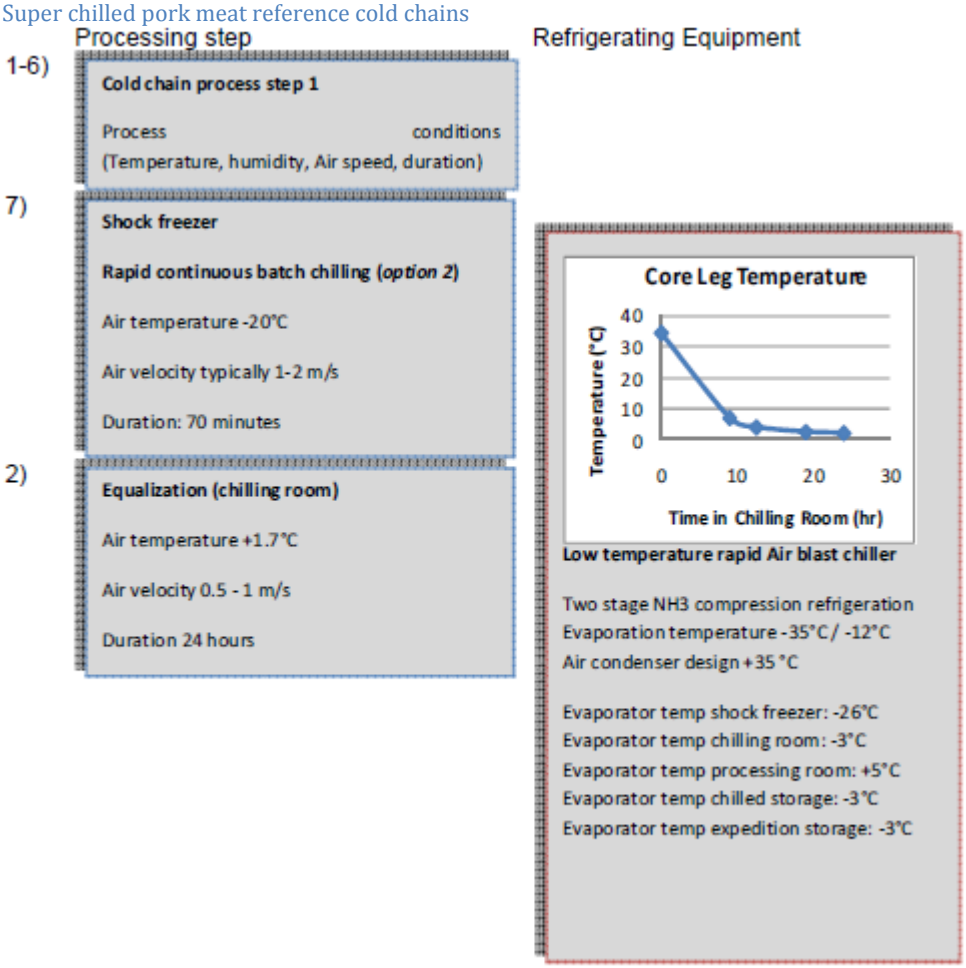
Process steps after expedition in the RTE pork meat cold chains.


Processing step
Refrigerating Equipment
X+1)
Refrigerated Road Transport
Air temperature +2 °C
Refrigerated road transport
Vapour compression refrigeration
Diesel powered
X+2)
Supermarket
Supermarket Refrigeration system
DX Vapour compression refrigeration
Supermarket Refrigerated Storage
Vapour compression refrigeration
Supermarket Refrigerated Display Case
Vapour compression refrigeration
2)
Transport (not conditioned)
By consumer, from supermarket to household
3)
Chilled Storage in household refrigerator
Air temperature +5 °C
Household Refrigerator
Vapour compression refrigeration

Super chilled pork meat cold chain

Sliced pork meat is a “candidate” for the super chilling process, which has so far been mostly applied to fish (salmon). The first part of the cold chain (steps 1 – 6), before entering the shock freezer, is identical to the pork carcass cold chain, described in paragraph 3.2. In this paragraph, the process before the Rapid continuous batch chilling process is assumed the same as that described for the pork carcass, and the further process starts with the rapid continuous batch chilling process (option 2), at an air temperature of -20°C (i.e. not equal to the typical temperature of -30°C as mentioned in paragr aph 3.2).

Super chilled pork meat reference cold chains



3)

Processing room; cutting (no packaging yet)

Air temperature +10 °C

Air velocity 0.1 – 0.5 m/s

Duration typically 30 minutes

The carcasses are parted, and different parts follow different processing.

Temperature neck in: 2.1 °C, Out 3.0 °C

Duration approximately 30 min

Pork neck unit weight: 3 kg, L=30cm (+/- 3 cm), Ø=15 cm (+/- 2 cm)

Low temperature rapid Air blast chiller

Two stage NH3 compression refrigeration

Evaporation temperature -35 °C / -12°C

Air condenser design +35 °C

Evaporator temp shock freezer: -26°C
Evaporator temp chilling room: -3°C
Evaporator temp processing room: +5°C
Evaporator temp chilled storage: -3°C
Evaporator temp expedition storage: -3°C

4)

Super chilling in special chilling rooms

Pork neck is placed on racks inside room

Air temperature -5 °C

Air velocity 1 - 2 m/s

Duration average 4 hours

HFC (R404A) refrigeration system for super chilling rooms.

Vapour compression refrigeration, R404A
Evaporation temperature -10 °C

5)

Cutting and packaging room

Air temperature +10 °C

Air velocity 0.5 - 1 m/s

Duration average 20 minutes

Pork neck is cut into cutlet and packed in consumer packaging. Unit weight 0.5 kg.

Consumer packaging's are packed in paper cartons (boxes) and put on pallets.

Neck cutlet temperature -2 °C in / -1.5 °C out

Packing material:
A-PET containers (Polyethylene terephthalate), top sealed. Modified atmosphere (60/40 CO_2/N_2).

Measure outside: 200x135x60 mm
Thermal conductivity: 0.15-0.24 W/mK
Thickness: 3 mm; headspace: 1 cm
Specific heat: 1900 J/kg.K; density: 1037 kg/m^3

6)

Super chilled product storage room

Air temperature -1,5 °C

Air velocity 0.5 - 1 m/s

Duration average 48 hours

Neck cutlet temperature -1.5 °C in / -1.5 °C out

Low temperature rapid Air blast chiller

Two stage NH3 compression refrigeration

7)

Expedition storage

Air temperature +2 °C

Air velocity 0.5 - 1 m/s

Duration average 12 hours

Neck cutlet temperature -1.5 °C in / -1 °C out

Low temperature rapid Air blast chiller

Two stage NH3 compression refrigeration

8)

Refrigerated Road Transport

Haugesund (N) to Oslo (455 km)

Air temperature +2 °C

Air velocity:

Duration average 6 hours

Neck cutlet temperature -1 °C in / -1 °C out

Refrigerated road transport

Vapour compression refrigeration

Diesel powered

9)

Distribution Center (Oslo)

Air temperature +2 °C

Air velocity:

Duration average 12 hours

Neck cutlet temperature -1 °C in / -1 °C out

Industrial Refrigeration System

Vapour compression refrigeration NH3

- Capacity for chilling (Air at +2 °C)
- Capacity for freezing (Air -18 °C)

10)

Refrigerated Road Transport

Oslo to supermarkets in Oslo region

Air temperature +2 °C

Air velocity:

Duration average 3 hours

Neck cutlet temperature -1 °C in / -1 °C out

Refrigerated road transport

Vapour compression refrigeration

Diesel powered

11)

Supermarket

Oslo region

Air temperature +4 °C

Air velocity:

Duration average 96 hours (4 days)

Neck cutlet temperature -1 °C in / 4 °C out

DX Supermarket Refrigeration system

Vapour compression refrigeration

Supermarket Refrigerated Storage

Vapour compression refrigeration

Supermarket Refrigerated Display Case

Vapour compression refrigeration

Salmon (chilled) cold chain

Chilled Salmon Reference Cold Chain

-)

Fish Farm (no temperature control)

Seawater normal temperatures (1–16 °C)

Living transport (fish carrier boat) to net cages outside slaugherhouse.

Pumping from net cages to drum chiller

Production: 8 hours per day

1)

Drum Chiller (outside, ambient temperature)

Living chilling in refrigerated sea water,

duration 50 min

Temp salmon in: 10 °C out: 4 °C

(10 °C is average, variation from 1 to 16 °C)

Mass in = mass out: 15 000 kg/h

Unit weight: 4 kg

2)

Bleeding Chiller (inside factory, ambient +10°C)

Killing of the fish and cutting of the throat.

Bleeding out in cleaned seawater (+1.5°C),

Duration: 40 min

Temp salmon in: 4 °C, Out 2 °C

Mass in: 15000 kg/h, mass out 14700 kg/ (300 kg (2 %) blood taken out as biowaste)

RSW (Refrigerated Sea Water) Drum Chiller

Drum chiller, 40 m^3:

Refrigerated seawater, +2°C.

5 % continuously replacement of seawater

RSW Bleeding chiller, 30 m^3:

Refrigerated sea water, +1.5°C.

15 % continuously replacement of seawater

Joint NH_3 compression system

Evaporator temp: -5°C

Condenser: Seawater 7°C (from fixed depth)

3) **Processing (inside factory, ambient +10°C)**

Temperature on salmon in: 2 °C, Out 3.5 °C

Mass in: 14700 kg/h

Gutting and filleting: Removal of head, guts, skin and bone. (6200 kg (40-45 %) biowaste)

Mass out 8500 kg/h

NH_3 seawater cooled refrigeration system

Common NH_3 compression system (2 stage) for air cooling to production room, fresh storage and freezing storage

Common for processing steps 3), 4) and 5)

4) **Packaging (inside factory, ambient +10°C)**

Temperature on salmon in: 3.5 °C

Mass in 8500 kg/h

Weighting and packing of filets in transport boxes together with ice. Temp reduction on salmon in boxes: From 3.5 to 0 °C,

5 kg salmon (average 1.13 kg pr filet) and 1.2 kg ice in each box.

NH_3 seawater cooled refrigeration system

Common NH_3 compression system (2 stage) for air cooling to production room, fresh storage and freezing storage

Evaporator temp production: 5°C?
Evaporator temp fresh storage: -5°C
Evaporator temp freezing storage: -35°C.
Condensing temperature: Seawater +7°C

5) **Storage (packed fresh products, ambient 0°C)**

Air temperature +0°C,

Average air speed 1-2 m/s

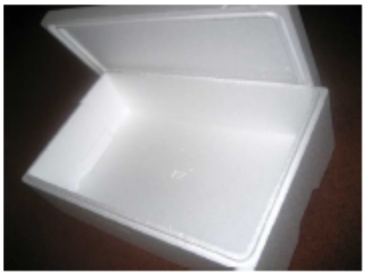
Average storage time: 24 hours

Temp salmon in: 0 °C, out 0 °C

Mass in = mass out: 8500 kg per hour

Packing material:

Expanded polystyrene boxes
Vartdal Standard 4306/6 (product 3 kg)
Measure outside: 400x300x100 mm
Measure inside: 360x260x65 mm
Heat resistance: 1.5-2.0 m^2K/W



Ice maker (separate NH3 system)

Evaporator temp: -10 °C

Condenser temp: +7 °C

2040 kg ice per hour

6)

Refrigerated Road Transport

North of Norway to Central Europe

Air temperature 0 °C

Air velocity:

Duration average 36 hours

Salmon temperature 0 °C in / 0 °C out

Refrigerated road transport

Vapour compression refrigeration

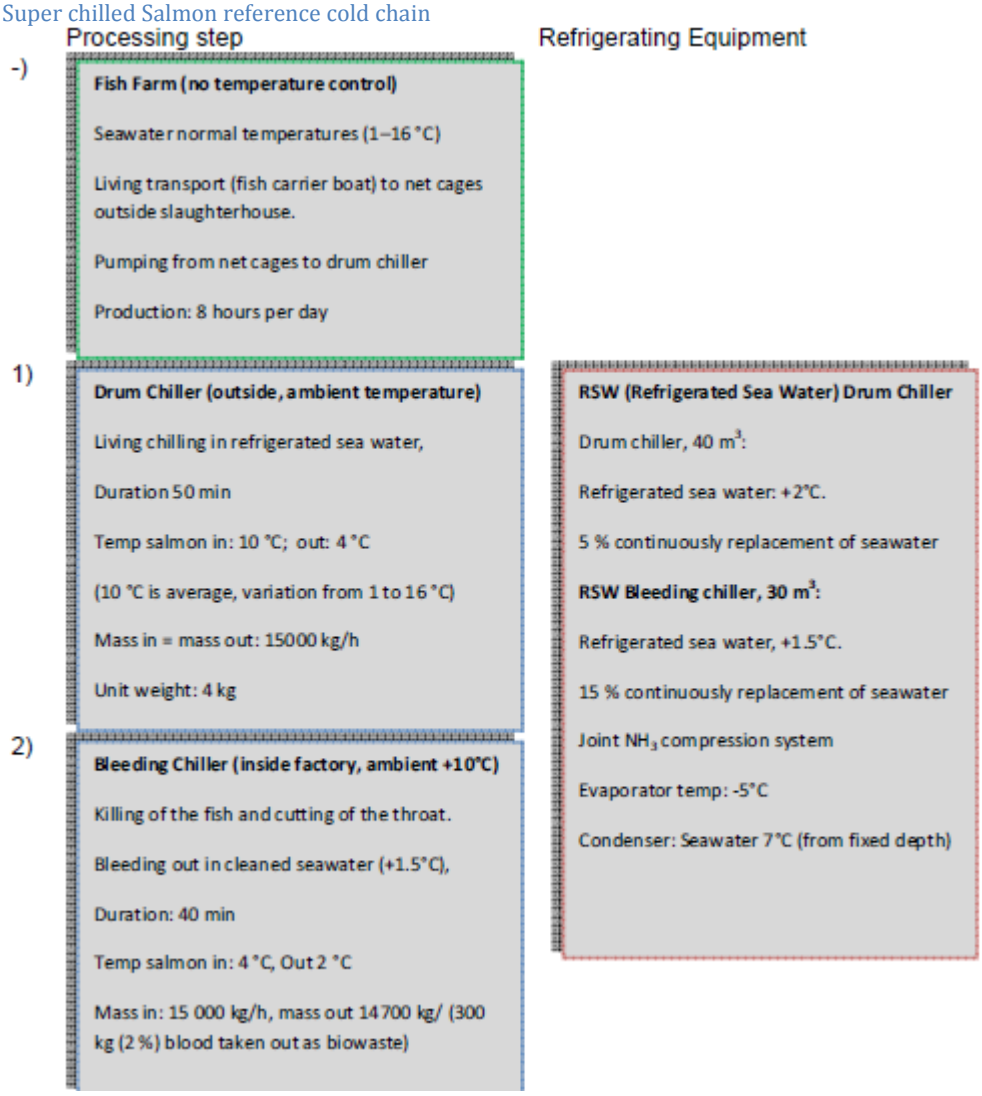
Diesel powered

7)

Distribution Center (central Europe)

Super chilled salmon cold chain

Super chilled Salmon reference cold chain


Processing step
Refrigerating Equipment
-)
Fish Farm (no temperature control)
Seawater normal temperatures (1–16 °C)
Living transport (fish carrier boat) to net cages outside slaughterhouse.
Pumping from net cages to drum chiller
Production: 8 hours per day
1)
Drum Chiller (outside, ambient temperature)
Living chilling in refrigerated sea water,
Duration 50 min
Temp salmon in: 10 °C; out: 4 °C
(10 °C is average, variation from 1 to 16 °C)
Mass in = mass out: 15000 kg/h
Unit weight: 4 kg
RSW (Refrigerated Sea Water) Drum Chiller
Drum chiller, 40 m3:
Refrigerated sea water: +2°C.
5 % continuously replacement of seawater
RSW Bleeding chiller, 30 m3:
Refrigerated sea water, +1.5°C.
15 % continuously replacement of seawater
Joint NH3 compression system
Evaporator temp: -5°C
Condenser: Seawater 7°C (from fixed depth)
2)
Bleeding Chiller (inside factory, ambient +10°C)
Killing of the fish and cutting of the throat.
Bleeding out in cleaned seawater (+1.5°C),
Duration: 40 min
Temp salmon in: 4 °C, Out 2 °C
Mass in: 15 000 kg/h, mass out 14700 kg/ (300 kg (2 %) blood taken out as biowaste)

3)

Processing (inside factory, ambient +10°C)

Temperature on salmon in: 2 °C, out 3.5 °C

Mass in: 14700 kg/h

Gutting and filleting: Removal of head, guts, skin and bone. (6200 kg (40-45 %) biowaste)

Mass out 8500 kg/h

Ammonia Refrigeration system

Common NH_3 compression system (2 stage) for air cooling to production room, fresh storage and freezing storage

Evaporator temp production: 5°C?
Evaporator temp fresh storage: -5°C
Evaporator temp freezing storage: -35°C.
Condensing temperature: Seawater +7°C

4)

Super chilling (with impingement freezer)

High speed airstream towards fish (-35°C, airspeed unknown)

Product temperature in: 3.5 °C, out -1.7 °C

Mass in = mass out: 8500 kg/h

Super chiller.

JBT Foodtech impingment freezer, Separate NH_3 compression system for surface freezing of salmon filets.

Heat transfer coeff. approx. 200 $W/m^2.K$

Evaporator temp: -35°C
Condensing temperature: Seawater +7°C

5)

Packing

Weighting and packing of filets in transport boxes.
Temp in = -1.7C, temp out: -1,5C
(Δh = -13.99 kJ/kg)

3.3 kg salmon (average 1.13 kg pr filet)
Mass in = mass out = 8500 kg/h

Packing material:
Expanded polystyrene boxes
Vartdal Standard 4306/6 (product 3 kg)
Measure outside: 400x300x100 mm
Measure inside: 360x260x65 mm
Heat resistance: 1.5-2.0 m^2K/W

6)

Storage (super chilled products, ambient -1,5°C)

Air temperature -1.5°C,

Average air speed 1-2 m/s

Average storage time: 24 hours

Temp salmon in: -1.7 °C, out -1.7 °C

Mass in = mass out: 8500 kg/h

7)

Refrigerated Road Transport

North of Norway to Central Europe

Air temperature -1.7 °C

Air velocity:

Duration average 36 hours

Salmon temperature -1.7 °C in / -1.7 °C out

Refrigerated road transport

Vapour compression refrigeration

Diesel powered

8)

Distribution Center (central Europe)

Spinach cold chain

Frozen spinach reference cold chain

	Processing step	Refrigerating Equipment
-)	**Harvesting** Harvesting period: April to end of October Ambient temperature: 2 to 25°C Spinach is harvested and partially cleaned mechanically and by air cleaner in the field. Harvesting is done 24 hours per day.	
-)	**Transport to processing plant** Spinach is transferred by truck (batch of 10 to 20 tons) to the plant. Transport duration: 15 minutes to 2 hours. Transport under ambient conditions.	

-) **Processing plant: cleaning**

Spinach is unloaded in outdoor reception tank,

Ambient temperature.

Cleaning process (not conditioned):

1. Air cleaner (to sort heavy foreign bodies...)

2. Descanter drum (to sort sand, earth, small insects...)

3. Pre Washer (to clean spinach), using water from final washer at temperature of: 20°C.

4. Optical sorter (camera and laser) to sort small foreign bodies leafs with default,

5. Final washer (to clean spinach) => Temperature water: 12°C to 20°C. Water consumption 12 m^3/h. Water isn't recycled.

Process capacity 10 tons of fresh spinach/hour.

-) **Processing plant: blanching**

Spinach is blanched in continuous blancher by spraying hot water (92°C) on spinach layer (80 mm). Water is heated by water steam (165°C). Steam is produced by a gas boiler.

Blancher Capacity: Inlet 10t/h, Outlet 7.5t/h

-) **Processing plant: cooling with water**

Spinach is cooled in continuous cooler by spraying cold water (12°C to 25°C). The water recirculates in a loop, when the water reaches 25°C it is drained.

-) **Visual inspection**

Spinach is visually inspected and controlled for quality.

-)

Hydraulic transport & forming

Spinach is transported by hydraulic transport (in water at 12°C) to forming machine.

Spinach is formed in cubic, rectangular, circular (and so on) shaped pellets. Medium weight of these pellets is 50 to 125 grams.

Vapour compression refrigeration system for air cooling

NH3 system (formerly R22)

Air temperature +15 °C

Supply to packaging & forming rooms

1)

Freezing Process from +12°C to -18°C

Spinach pellets are frozen in spiral freezer with air at -27°C.

Air velocity = 0.3 to 0.6 m/s.

Freezing time to -18°C = 45 minutes to 1 hour.

Ammonia Refrigeration system with evaporative condenser

NH_3 compression system

Evaporator temp freezing storage: -35°C. Evaporative condenser (ambient air + water at +12°C)

2)

Packaging Process

Process in conditioned room (+15°C)

Frozen spinach pellets are packed in bags with a weight varying from 1 kg to 2.5 kg. Bags are packed in cardboard box (4 to 10 bags per box).

Palettisation before transfer to cold store (Palett is waiting 1 hour in 15°C).

Vapour compression refrigeration system for air cooling

NH3 system (formerly R22)

Air temperature +15 °C

Supply to packaging & forming rooms

3)

Cold Storage

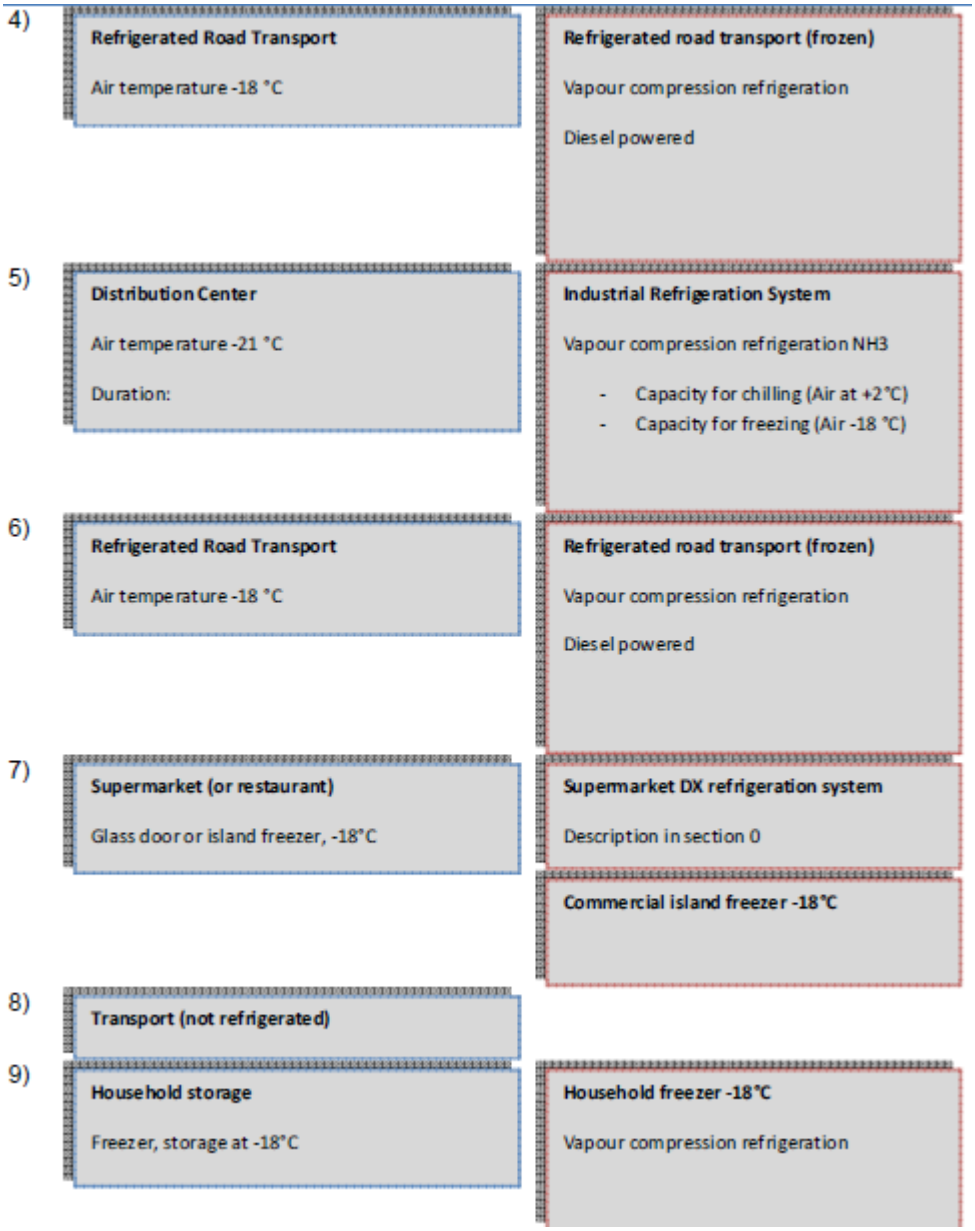
Storage in cold store (-18°C)

Storage duration: some days to one year.

Ammonia Refrigeration system with evaporative condenser

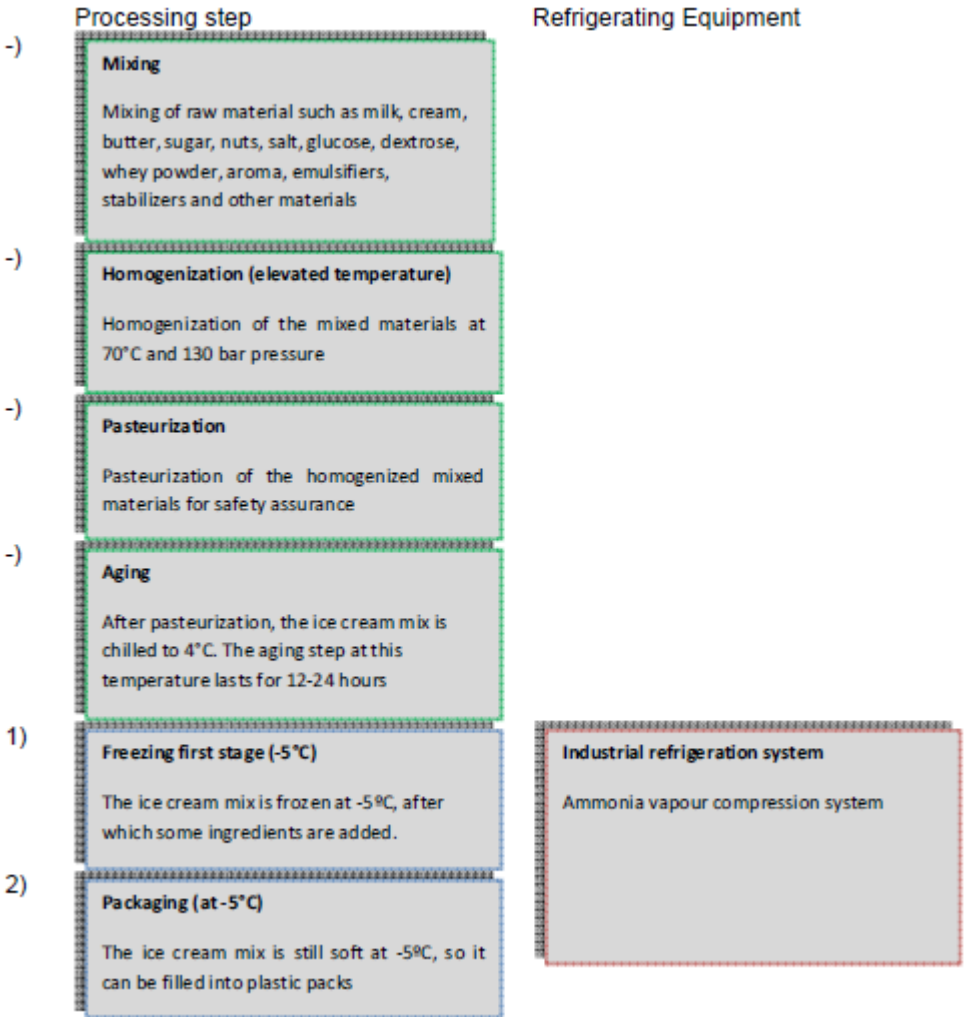
NH_3 compression system

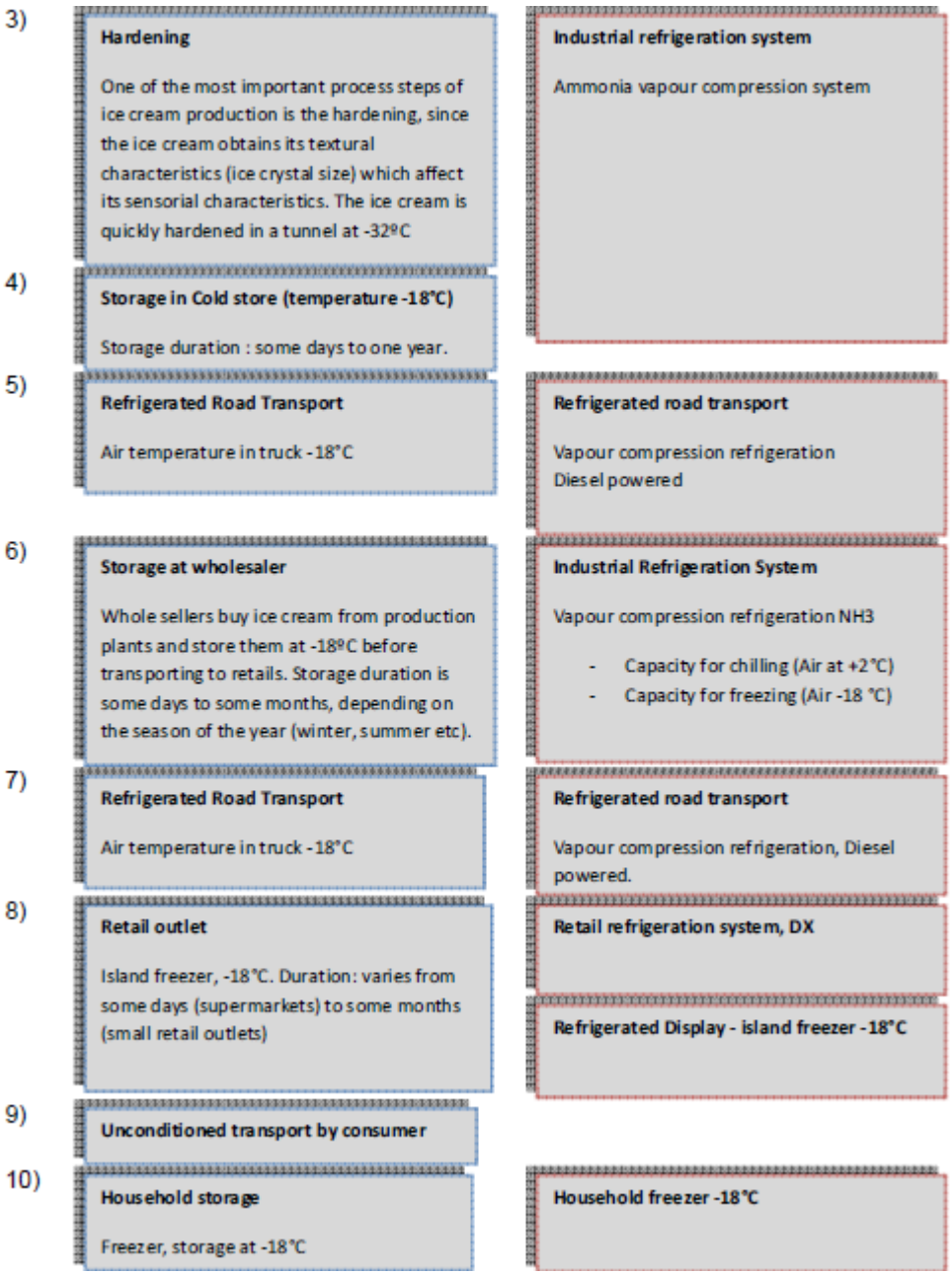
Evaporator temp freezing storage: -35°C. Evaporative condenser (ambient air + water at +12°C)


4)
Refrigerated Road Transport
Air temperature -18 °C
Refrigerated road transport (frozen)
Vapour compression refrigeration
Diesel powered
5)
Distribution Center
Air temperature -21 °C
Duration:
Industrial Refrigeration System
Vapour compression refrigeration NH3
- Capacity for chilling (Air at +2°C)
- Capacity for freezing (Air -18 °C)
6)
Refrigerated Road Transport
Air temperature -18 °C
Refrigerated road transport (frozen)
Vapour compression refrigeration
Diesel powered
7)
Supermarket (or restaurant)
Glass door or island freezer, -18°C
Supermarket DX refrigeration system
Description in section 0
Commercial island freezer -18°C
8)
Transport (not refrigerated)
9)
Household storage
Freezer, storage at -18°C
Household freezer -18°C
Vapour compression refrigeration

Ice cream cold chain

Ice Cream reference cold chain


Processing step
Refrigerating Equipment
-)
Mixing
Mixing of raw material such as milk, cream, butter, sugar, nuts, salt, glucose, dextrose, whey powder, aroma, emulsifiers, stabilizers and other materials
-)
Homogenization (elevated temperature)
Homogenization of the mixed materials at 70°C and 130 bar pressure
-)
Pasteurization
Pasteurization of the homogenized mixed materials for safety assurance
-)
Aging
After pasteurization, the ice cream mix is chilled to 4°C. The aging step at this temperature lasts for 12-24 hours
1)
Freezing first stage (-5°C)
The ice cream mix is frozen at -5ºC, after which some ingredients are added.
Industrial refrigeration system
Ammonia vapour compression system
2)
Packaging (at -5°C)
The ice cream mix is still soft at -5ºC, so it can be filled into plastic packs


3)
Hardening
One of the most important process steps of ice cream production is the hardening, since the ice cream obtains its textural characteristics (ice crystal size) which affect its sensorial characteristics. The ice cream is quickly hardened in a tunnel at -32ºC
Industrial refrigeration system
Ammonia vapour compression system
4)
Storage in Cold store (temperature -18°C)
Storage duration : some days to one year.
5)
Refrigerated Road Transport
Air temperature in truck -18°C
Refrigerated road transport
Vapour compression refrigeration
Diesel powered
6)
Storage at wholesaler
Whole sellers buy ice cream from production plants and store them at -18ºC before transporting to retails. Storage duration is some days to some months, depending on the season of the year (winter, summer etc).
Industrial Refrigeration System
Vapour compression refrigeration NH3
- Capacity for chilling (Air at +2°C)
- Capacity for freezing (Air -18 °C)
7)
Refrigerated Road Transport
Air temperature in truck -18°C
Refrigerated road transport
Vapour compression refrigeration, Diesel powered.
8)
Retail outlet
Island freezer, -18°C. Duration: varies from some days (supermarkets) to some months (small retail outlets)
Retail refrigeration system, DX
Refrigerated Display - island freezer -18°C
9)
Unconditioned transport by consumer
10)
Household storage
Freezer, storage at -18°C
Household freezer -18°C

Quality models

A summary of the quality models implemented in the FRISBEE tool is shown in the table below:

Apple

Quality indicator	Model structure	Model variables		Model parameter		Model validity range
		Variable	Meaning	Parameter	Estimate	
[1]Firmness	$\frac{\mathrm{d}[P]}{\mathrm{d}t} = -k_{pect}[P][E_{pect}]$ $\frac{d[E_{pect}]}{dt} = k_{E_{pect}}[Eth] - k_{E_{den}}[E_{pect}]$ $\frac{\mathrm{d}[Eth]}{\mathrm{d}t} = \frac{V_{m,Eth} p_{O_2} \sqrt{\frac{[Eth]}{[Eth]_{ref}}}}{K_{m,O_2,Eth} + p_{O_2}\left(1 + \frac{p_{CO_2}}{K_{mu,CO_2,Eth}}\right)} + k_{Eth}\left([Eth]_{\infty} - [Eth]\right)$ $k_i = k_{i,ref} \exp\left(\frac{E_{a,i}}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)$ $F = F_c + \gamma[P]$ $\phi_{Eth} = \frac{P_{Eth} A [Eth]}{m}$	F (N) $[P]$ $[E_{pect}]$ $[Eth]$ T (°C) t (d)	Firmness Pectin integrity Pectin degrading enzyme Internal ethylene concentration Temperature Time	$k_{pect,ref}$ $k_{E_{pect},ref}$ $k_{E_{deg},ref}$ $V_{m,Eth}$ $[Eth]_{ref}$ $K_{m,O_2,Eth}$ $K_{mu,CO_2,Eth}$ k_{Diff} m $E_{a,pect}$ $E_{a,E_{pect}}$ $E_{a,E_{deg}}$ R T_{ref} F_c γ	0.00027 d^{-1} $nmol^{-1}$ 0.00029 d^{-1} 0.1 d^{-1} 13.51 mmol d^{-1} 1 4.44 kPa 0.76 kPa 0.0014 d^{-1} 0.2 kg 90021 J mol^{-1} 59798 65241 J mol^{-1} 8.314 J mol^{-1} K^{-1} 10 °C 39.44 N 1254 N $mmol^{-1}$	0 °C to 25 °C 1 % to 21 % O_2 0 % to 10 % CO_2
[2]Background skin colour	$\frac{\mathrm{d}[Chl]}{\mathrm{d}t} = -k_{Chl}[Chl][Chlase]$ $\frac{\mathrm{d}[Chlase]}{\mathrm{d}t} = k_{Chlase}[Eth] - k_{Chlase_{deg}}[Chlase]$	a^* $[Chl]$ $[Chlase]$ $[Eth]$ T (°C) t (d)	a* -value of the CIE Chlorophyll concentration Chlorophyllase enzyme Internal ethylene concentration Temperature Time	k_{Chl} k_{Chlase} $k_{Chlase_{deg}}$ $V_{m,Eth}$ $[Eth]_{ref}$ $K_{m,O_2,Eth}$ $K_{mu,CO_2,Eth}$	0.21 d^{-1} $nmol^{-1}$ 0.0023 d^{-1} 0.73 d^{-1} 13.51 1 4.44 0.76	0 °C to 25 °C 1 % to 21 % O_2 0 % to 10 % CO_2

$$\frac{\mathrm{d}[Eth]}{\mathrm{d}t} = \frac{V_{m,Eth}\, p_{O_2} \sqrt{\frac{[Eth]}{[Eth]_{ref}}}}{K_{m,O_2,Eth} + p_{O_2}\left(1 + \frac{p_{CO_2}}{K_{mu,CO_2,Eth}}\right)} + k_{Eth}\left([Eth]_{\infty} - [Eth]\right)$$

$$k_i = k_{i,ref} \exp\left(\frac{E_{a,i}}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)$$

$$a^* = a_c + \alpha[Chl]$$

$$\phi_{Eth} = \frac{P_{Eth} A [Eth]}{m}$$

k_{Diff}	0.0014	
m	0.2	
$E_{a,Chl}$	35323 J mol^{-1}	
$E_{a,Chlase}$	119080 J mol^{-1}	
$E_{a,Eth}$	71403 J mol^{-1}	
R	8.314 J mol^{-1} K^{-1}	
T_{ref}	10 °C	
a_c	11.55	
α	-3.07	

Weight loss

$$\frac{\mathrm{d}m}{\mathrm{d}t} = k_{ta} A (p - p_{\infty})$$

$$p = \frac{m_{H_2O} P_{sat} x_w}{RT}$$

p (kg m^{-3})	water vapour density of apple	k_{ta}	0.1825 d^{-1}	1 °C to 25 °C
p_{∞} (kg m^{-3})	water vapour density of surrounding atmosphere	A	0.02 m^2	0 to 100 % RH
T (°C)	Temperature	m_{H_2O}	18 × 10^{-3}	
m (kg)	Unit mass of apple	R	8.314 J mol^{-1} K^{-1}	
P_{sat} (Pa)	Saturated vapour pressure			
x_w	Moisture content			
t (d)	Time			

Modified atmosphere packed cooked ham, and Modified atmosphere packed cooked pâté

Quality indicator	Model structure	Model variables		Model parameter			Model validity range
		Variable	Meaning	Parameter	Estimate Ham	Pâté	
[3]*L. monocytogenes*	$\begin{cases} \frac{dN}{dt} = 0 & if\ t \le lag \\ \frac{dN}{dt} = \mu_{\max} N\left(1 - \frac{N}{N_{\max}}\right) & if\ t > lag \end{cases}$	N (log CFU/g)	Population count	μ_{opt}	0.7525 h^{-1}	0.7537 h^{-1}	pH for ham: 6.31± 0.04 aw for ham: 0.980 ±0.005 pH for pâté 6.45±0.01 aw for pâté : 0.986 ±0.003 5 °C to 15 °C
		T (°C)	Temperature	$lag_{\min}$	3.55 h	1.17 h	
		t (h)	Time	$\gamma(pH)$	0.9329	0.9574	
				$\gamma(a_w)$	0.6212	0.7902	

	$\mu_{opt} = \frac{\mu_{\max}}{\gamma(T)\gamma(pH)\gamma(a_w)\gamma(\text{int})}$ $lag = \frac{lag_{\min}}{\gamma(T)\gamma(pH)\gamma(a_w)\gamma(\text{int})}$ $\gamma(T) = \begin{cases} \frac{(T-T_{\max})(T-T_{\min})^2}{(T_{opt}-T_{\min})\left[(T_{opt}-T_{\min})(T-T_{opt})-(T_{opt}-T_{\max})(T_{opt}+T_{\min}-2T)\right]} & \text{for } T_{\min} < T < T_{\max} \\ 0 & \text{Otherwise} \end{cases}$			$\gamma(\text{int})$	1	1	
				$N_{\max}$	9.11 log CFU/g	9.18 log CFU	
				$T_{\min}$	-2.47 °C	-2.47 °C	
				T_{opt}	38.2 °C	38.2 °C	
				$T_{\max}$	43.3 °C	43.3 °C	
[4]*Lc. mesenteroïdes* 74	$\begin{cases} \frac{dN}{dt} = 0 & if\ t \le lag \\ \frac{dN}{dt} = \mu_{\max} N\left(1-\frac{N}{N_{\max}}\right) & if\ t > lag \end{cases}$ $\mu_{opt} = \frac{\mu_{\max}}{\gamma(T)}$ $lag = \frac{lag_{\min}}{\gamma(T)}$ $\gamma(T) = \begin{cases} \frac{(T-T_{\max})(T-T_{\min})^2}{(T_{opt}-T_{\min})\left[(T_{opt}-T_{\min})(T-T_{opt})-(T_{opt}-T_{\max})(T_{opt}+T_{\min}-2T)\right]} & \text{for } T_{\min} < T < T_{\max} \\ 0 & \text{Otherwise} \end{cases}$	N (log CFU/g)	Population count	μ_{opt}	0.6029 h^{-1}	0.6521 h^{-1}	pH for ham: 6.43± 0.04 aw for ham: 0.980 ±0.006 pH for pâté 6.45±0.01 aw for pâté : 0.984 ±0.004 5 °C to 15 °C μ_{opt} includes pH and aw effects
		T (°C)	Temperature	$lag_{\min}$	0.17 h	0.79 h	
		t (h)	Time	$N_{\max}$	9.07 log CFU/g	9.18 log CFU	
				$T_{\min}$	-0.53 °C	-0.53°C	
				T_{opt}	28.04 °C	28.04 °C	
				$T_{\max}$	36.05 °C	36.05 °C	
[4]*Lb. sakei 1322*	$\begin{cases} \frac{dN}{dt} = 0 & if\ t \le lag \\ \frac{dN}{dt} = \mu_{\max} N\left(1-\frac{N}{N_{\max}}\right) & if\ t > lag \end{cases}$ $\mu_{opt} = \frac{\mu_{\max}}{\gamma(T)}$ $lag = \frac{lag_{\min}}{\gamma(T)}$	N (log CFU/g)	Population count	μ_{opt}	1.3408 h^{-1}	1.1804 h^{-1}	pH for ham: 6.43± 0.04 aw for ham: 0.980 ±0.006 pH for pâté 6.45±0.01 aw for pâté : 0.984 ±0.004 5 °C to 15 °C μ_{opt} includes pH and aw effects
		T (°C)	Temperature	$lag_{\min}$	0.58 h	3.0 h	
		t (h)	Time	$N_{\max}$	8.91 log CFU/g	8.67 log CFU	
				$T_{\min}$	0.25°C	0.25 °C	
				T_{opt}	33.02 °C	33.02 °C	

$$\gamma(T)=\begin{cases}\dfrac{(T-T_{max})(T-T_{min})^2}{(T_{opt}-T_{min})\left[(T_{opt}-T_{min})(T-T_{opt})-(T_{opt}-T_{max})(T_{opt}+T_{min}-2T)\right]} & \text{for } T_{min}<T<T_{max}\\ 0 & \text{Otherwise}\end{cases}$$

T_{max}	39.12 °C	39.12 °C	

Frozen pork neck cutlet

Quality indicator	Model structure	Model variables		Model validity range
		Variable	Meaning	
Drip loss	$\frac{dY}{dt}=0.2607e^{(0.1096T)}$	Y (%)	Drip loss	-18°C to -1°C
		T (°C)	Temperature	
		t (d)	Time	

Salmon fillets

Quality indicator	Model structure	Model variables		Model validity range
		Variable	Meaning	
Spoilage lactic acid bacteria	$N=N_0e^{k(t-\lambda)}$ $k=0.9732e^{0.2497T}$ $\lambda=5.55731e^{-0.31T}$	N	Inoculum	-1.7°C to 2°C
		T (°C)	Temperature	
		t (d)	Time	

Ice cream

Quality indicator	Model structure	Model variables		Model parameter		Model validity range
		Variable	Meaning	Parameter	Value	
[5]Sensory perception	$S_{icecrystals}=So+a\left(1+\exp(-kt)\right)$ $a=a_{ref}\exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$ $k=k_{ref}\exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$	S	Score for overall acceptability (1-9)	S_o	1	-5 °C to -30 °C
		T (°C)	Temperature	S_f	6.5	
		t (d)	Time	E_a [a(T)]	51.4 kJ mol^{-1}	
				a_{ref}	2.10	
				k_{ref}	0.0082 d^{-1}	
				E_a [k(T)]	78.1 kJ mol^{-1}	
				T_{ref}	-18°C	
[5]Viscoelasticity/ Damping factor	$\tan\delta_{T_{ref}=-8}=C_1+C_2e^{(-kt)}$	$\tan\delta_{T_{ref}=-8}$	Damping factor measured at reference temperature -8°C	$\tan\delta_f$	0.76	-5 °C to -30 °C
		T (°C)	Temperature	C_1	0.76	

	$k = k_{ref} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$	t (d)	Time	C_2	0.40
				k_{ref}	0.0211
				E_a	23.1 kJ mol^{-1}
				T_{ref}	-18°C
[5]Firmness	$F_{t,T} = F_{t_0,T} + k * t$ $k = k_{ref} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$	F (g) T (°C) t (d)	Firmness Temperature Time	F_{to} F_f E_a k_{ref} T_{ref} R	873 g 6000 g 47.5 kJ mol^{-1} 23.2 d^{-1} -12°C 8.314 J mol^{-1} K^{-1}

Spinach leaves

Quality indicator	Model structure	Model variables		Model parameter		Model validity range
		Variable	Meaning	Parameter	Values	
[6]Vitamin C content	$C = C_0 e^{-kt}$ $k = k_{ref} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$	C (mg/100g) T (°C) t (d)	Vitamin C/L-ascorbic acid content Temperature Time	C_0 C_f E_a k_{ref} T_{ref} R	25.89 mg/100g 7.77 mg/100g 132.0 kJ mol^{-1} 0.0029 d^{-1} -18°C 8.314 J mol^{-1} K^{-1}	-5 °C to -30 °C
[6]Chlorophyll content	$C = C_0 e^{-kt}$ $k = k_{ref} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$	C (mg/100g) T (°C) t (d)	Total chlorophyll content (mg/100g) Temperature Time	C_0 C_f E_a k_{ref} T_{ref} R	37.4 mg/100g 22.4 mg/100g 70.3 kJ mol^{-1} 0.0011 d^{-1} -18°C 8.314 J mol^{-1} K^{-1}	-5 °C to -30 °C
[6]Sensory evaluation	$S = S_0 - (k_{sensoryattribute} * t)$	S	Score for overall acceptability (1-9)	S_0	9	-5 °C to -30 °C

$k = k_{ref} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]$	T (°C)	Temperature	S_f	6
	t (d)	Time	E_a	61.26 kJ mol^{-1}
			k_{ref}	0.0077 d^{-1}
			T_{ref}	-18°C
			R	8.314 J mol^{-1} K^{-1}

Table S1. Model structure, model parameter values, and validity range of the quality models implemented in the FRISBEE tool

[1] For details of model development and experimental design, see Gwanpua et al. (2013).

[2] For details of model development and experimental design, see Gwanpua et al. (2014).

[3] For details of model development and experimental design, see Stahl et al. (2014). T_{opt} and $T_{\max}$ were obtained from Couvert et al. (2010), while $T_{\min}$ was obtained from Pouillot et al. (2003)

[4] For details of model development and experimental design, see Stahl et al. (2014).

[5] For details of model development and experimental design, see Tsevdou et al. (2014).

[6] For details of model development and experimental design, see Dermesonluoglu et al. (2014).

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Heat Load Calculations

The main factors that contributed to the heat load were the product load (*kg*), area of the walls, floor and ceiling, type and thickness of insulators, door dimensions, number and frequency of door openings, relative humidity outside (RH_{out}) and inside (RH_{in}) the storage rooms, temperature outside (T_{out}) and inside (T_{in}) the storage rooms, rate of respiration, and expected weight loss.
The heat of respiration was given by;

$$Q_{resp} = m \times a \times e^{\left(\frac{b \times T_{cold}}{1000}\right)}$$
$$where;\ \ m = product\ load$$
$$a = 15.148\ \ and\ \ b = 0.097$$

The respiratory parameters a and b are specific for apples.
The heat transmission through the walls, ceiling and floor was given by;

$$Q_{trans} = \left(U_{wall} \times A_{wall} \times (T_{out} - T_{cold})\right) + \left(U_{ceiling} \times A_{ceiling} \times (T_{out} - T_{cold})\right) + \left(U_{floor} \times A_{floor} \times (T_{floor} - T_{cold})\right)$$

Where:

- $U_{wall}\ (W/m^2.K)$ was the overall heat transfer coefficient of the walls of the cold room, given by;

  $$U_{wall} = \frac{1}{\left(\frac{1}{h_{in}} + \frac{x_{wall}}{k_{wall}} + \frac{1}{h_{out}}\right)}$$

  - With
  - h_{in} the surface heat transfer coefficient inside the cold room given as $9.3W/m^2.K$
  - x_{wall} the thickness of the wall insulation given in m
  - k_{wall} the conductive heat transfer coefficient of the insulator $(W/m\,K)$
  - With h_{out} the surface heat transfer coefficient outside the cold room given as $9.3W/m^2.K$ (assuming no wind movements with the envelop of the storage facility)
- $U_{ceiling}\ (W/m^2K)$ was the overall heat transfer coefficient of the roof of the cold room, given by;

  $$U_{ceiling} = \frac{1}{\left(\frac{1}{h_{in}} + \frac{x_{ceiling}}{k_{ceiling}} + \frac{1}{h_{out}}\right)}$$

  - $x_{ceiling}$ is the thickness of the roof insulation given in m
  - $k_{ceiling}$ is the conductive heat transfer coefficient of the insulator
- $U_{ceiling}\ (W/m^2.K)$ is the overall heat transfer coefficient of the roof of the cold room, given by;

  $$U_{floor} = \frac{1}{\left(\frac{1}{h_{in}} + \frac{x_{floor}}{k_{floor}} + \frac{x_{wear}}{k_{wear}}\right)}$$

- x_{floor} is thickness of the floor insulation given in m
- k_{floor} is the conductive heat transfer coefficient of the insulator
- x_{wear} is thickness of the wearing surface
- k_{cwear} is the conductive coefficient of the wearing surfae

- A_{wall} (m^2) is the total wall area in contact with the outside air temperature.
- $A_{ceiling}$ (m^2) is the total wall area in contact with the outside air temperature.
- A_{floor} (m^2) is the total wall area in contact with the outside floor temperature.

For the heat load that resulted from the defrost unit, the following equation was used for the computation:

$$Q_{defrost} = \frac{((mDO \times (X_{out} - X_{in}) \times LF \times durOpen \times nOpen) + (wt_{loss} \times LF))}{(1 - D_{eff}) \times 24 \times 3600}$$

Where;

- mDO is the mass flow rate through the open door (kg/s)
- X_{out} is the outside absolute humidity computed from the T_{out} and RH_{out}.
- X_{in} is the absolute humidity inside the storage room computed from the T_{cold} and the relative humidity in the storage room (RH_{in}).
- $durOpen$ and $nOpen$ are the duration and frequency of door openings respectively.
- wt_{loss} is the weight loss in (kg/day)
- $LF\,(J/kg)$ is the latent heat of fusion of water, given as $334000 J/kg$
- D_{eff} is the efficiency of the defrost unit

The heat load that resulted from door opening as well as the door seals was computed using the equation below:

$$Q_{doors} = \frac{(Qs_{DO} + Ql_{DO}) + durOpen \times nOpen}{24 \times 3600} + Qs_{seal} + Ql_{seal}$$

Where:

- Qs_{DO} is the sensible heat load from the door opening and depends on mDO, T_{cold}, T_{out} and the specific heat capacity of air, $Cp_{air} = 1005\, J/kg.K$.
- Ql_{DO} is the is the latent heat load from door opening and depends on mDO, X_{out}, X_{in}, LF and the latent heat of vaporisation of water, $LV = 2500000 J/kg$.
- Qs_{seal} is the sensible heat load through the door seals and depends T_{cold}, T_{out} Cp_{air} and the mass flow rate through the door seals, mDS in kg/s.
- Ql_{seal} is the is the latent heat load through door seals and depends on mDS, X_{out}, X_{in}, LF and LV.

The heat load from the evaporator fans was also accounted for using the equation below;

$$Q_{fan} = \frac{P_{evap} \times (Q_{resp} + Q_{trans} + Q_{defrost} + Q_{door})}{1000}$$

Where P_{evap} is the fan power given in W. Each storage cell contained four evaporator fans for air cooling as well as defrost system which could be alternated.

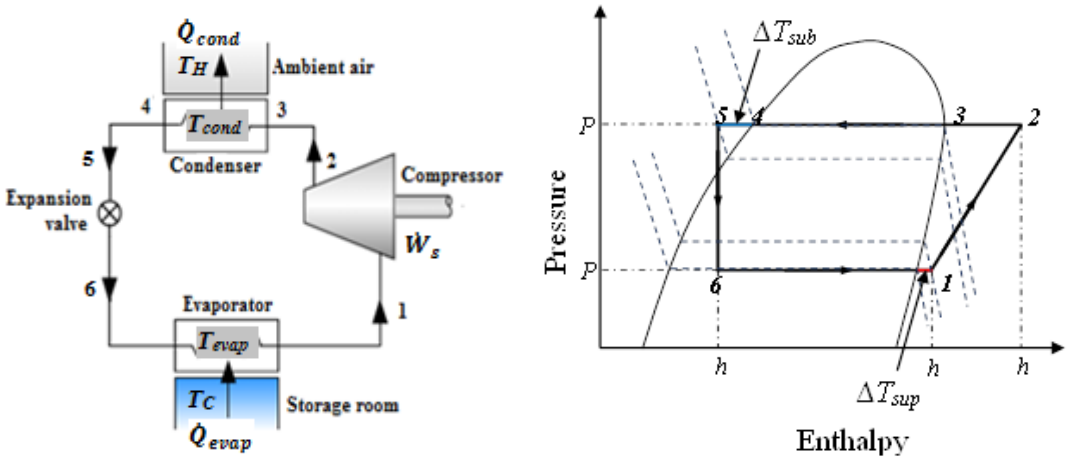
The heat load produced by lighting within the cold room was is also assumed to be zero.

The total heat load in required to be removed by the system during the desired storage duration was thus given by:

$$Heat\ Load = Q_{resp} + Q_{trans} + Q_{defrost} + Q_{door} + Q_{fan}$$

Cooling Requirements

Cooling involved the removal of the entire heat load within the storage rooms. For this studies, the cooling was achieved through the vapour compression cycle. This cycle transferred heat energy from the region of low temperature (inside the storage rooms), to the region of higher temperature (outdoor) using a working fluid (refrigerant). A schematic diagram of a vapour compression cycle is shown below:



(A) (B)

Conventional vapour compression cycle

The working principle of a refrigeration cycle was based on the following: Low pressure super-heated vapour (1) was compressed isentropically (1-2) to a high pressure vapour with high temperature (3) by the compressor. This compression was achieved by supplying work (W_s) to the compressor. This hot vapour stream was then cooled to the saturation temperature in the first part of the condenser (2-3) by removing the superheat, condensed isothermally in the middle part (3-4), and sub-cooled in the last part (4-5) to give the liquid (5). The pressure was then lowered isenthalpically to its original value in the expansion valve, resulting in a two-phase mixture (1). This mixture was then vaporized isothermally and then heated in the evaporator to give a super-heated vapour, and hence closing the cycle.

For this studies, we considered a one-stage direct-expansion system with multiple evaporators distributed in the various storage rooms. The flow of refrigerant to the various evaporators was regulated by independent controllers. Since it was difficult to keep track of the temperature of the refrigerant in the evaporator and condenser, we used a desired temperature difference between both the evaporator and condenser, and their surrounding air.

At the evaporator, the intended temperature difference between the storage room and the temperature of the evaporating fluid was denoted ΔT_{evap} and was given in °C. At the evaporator inlet, the saturation temperature of the refrigerant (T_{evap}) was calculated by subtracting ΔT_{evap} from the set storage temperature (T_{cold}). This T_{evap} also corresponded to the inlet temperature of the evaporator, T_{evap_in}. The T_{evap_in} was intend used to compute the saturation pressure at the evaporator (P_{evap}). But using this to compute the enthalpy was difficult because this region consisted of a mixture of liquid and vapour, and we didn't know yet the proportions of this mixture. Hence we had to rely on computing the condenser outlet enthalpy, which was assumed to be isenthalpic with this region.

At the outlet of the evaporator, the temperature was increased by a factor called the evaporator superheat (ΔT_{sup}) to give the evaporator outlet temperature, T_{evap_out}. This T_{evap_out} was then used to compute the evaporator outlet enthalpy, H_{evap_out}.

Inlet: $T_{evap\_in} = T_{cold} - \Delta T_{evap}$

$P_{evap} = f(Refrigerant, T_{evap\_in})$

Outlet: $T_{evap\_out} = T_{evap\_in} + \Delta T_{sup}$

$H_{evap\_out} = f(Refrigerant, P_{evap}, T_{evap\_out})$

Similarly at the condenser, the intended temperature difference between the condensing fluid and the surrounding ambient air was denoted ΔT_{cond} and was given in °C. At the inlet of the condenser, the fluid was in the superheated form. The fluid was assumed to have undergone a non-isentropic compression at the compressor, with a certain isentropic efficiency, eff_{is}. The suction pressure and enthalpy of the compressor corresponded to the evaporation pressure (P_{evap}) and evaporator outlet enthalpy (H_{evap_out}), respectively. The discharge temperature was calculated from P_{evap} and H_{evap_out}, and also depended on the type of refrigerant used. This discharge temperature and enthalpy corresponded to the condenser inlet temperature (T_{cond_in}) and condenser inlet enthalpy (H_{cond_in}), respectively.

In the middle part where isothermal condensation occurred, the condensation temperature of the refrigerant (T_{cond}) was calculated by adding ΔT_{cond} to the ambient air temperature (T_{hot}). T_{cond} was then used to compute the condensation pressure of the condenser (P_{cond}). At the outlet of the condenser, the temperature was decreased by a factor called the condenser subcool (ΔT_{sub}) to give an outlet temperature T_{cond_out}. This T_{cond_out} was then used to compute the condenser outlet enthalpy, H_{cond_out}.

Inlet: $T_{cond\_in} = f(refrigerant, P_{evap}, H_{evap\_out})$

$H_{cond\_in} = f(refrigerant, P_{evap}, T_{cond\_in}, P_{cond}, eff_{is})$

Outlet: $T_{cond} = T_{hot} + \Delta T_{cond}$

$P_{cond} = f(refrigerant, T_{cond})$

$T_{cond\_out} = T_{cond} - \Delta T_{sub}$

$H_{cond\_out} = f(Refrigerant, T_{cond\_out})$

As earlier mentioned, the condenser outlet and the evaporator inlet were assumed to be isenthalpic; hence the evaporator inlet enthalpy and the condenser outlet enthalpy are equal.

$H_{evap\_in} = H_{cond\_out}$

The COP is defined as the ratio of the heat load removed to the electrical power consumed as work by the compressor. A higher COP will mean a lower operating cost for the system. The efficiency of the compressor motor (eff_{motor}) also influences the COP. The higher the eff_{motor}, the higher COP and

vice-versa. The COP was calculated from the changes in enthalpy in the evaporator and compressor, and the motor efficiency.

$$COP_c = \frac{H_{evap\_out} - H_{evap\_in}}{H_{cond\_in} - H_{evap\_out}} \times eff_{motor}$$

COP_c denoted the COP of the compressor, which involved solely removal of the heat load within the storage rooms. Generally, the COP should include all addition loads incurred from ancillary components such as the condenser fans, pump and evaporator fans. Hence the equation for computing the overall COP is written thus;

$$COP = \frac{1}{\frac{1}{COP_C} + W}$$

Where W is the sum of the power of all ancillary components in kW. W consistutes the evaporator fan power (P_{evap}), condenser fan power (P_{cond}) and pump power (P_{pump}). This determines the amount of heat load which is removed from the system as work (electrical power).

Total Energy

The energy used was calculated from the heat load, together with the additional load incurred from the ancillary components such as the condenser fans, pump and evaporator fans. Converting this to electrical energy terms was attained by dividing the heat load by the COP. The energy used was measured in kWh.

$$E_{used} = \frac{(Heat\ Load)}{COP}$$

Global warming impact assessment

TEWI stands for Total Equivalent Warming Impact. The concept was developed as a comparative index of the global warming impacts of applications by accounting for both the direct contributions from refrigerants and the indirect contributions from energy consumption. It provides a useful tool to compare various technologies. The calculation and definition of the TEWI value is:

$$TEWI = \underbrace{\underbrace{GWP \cdot L/100 \cdot n \cdot m}_{Leakage} + \underbrace{GWP \cdot m \cdot (1-\alpha)}_{Recovery\ losses}}_{Direct\ emissions} + \underbrace{\underbrace{n \cdot E_{annual} \cdot \beta}_{Energy\ consumption}}_{Indirect\ emissions}$$

where

- GWP : Global Warming Potential of the refrigerant. GWP values depend on the infrared absorption properties of the gas and the elapsed time before it is purged from the atmosphere
- L : leakage rate per year (%/year)
- n : operating life (years)
- m : refrigerant charge (kg)
- a : recycling factor (%)
- E_{annual} : energy consumption per year (kWh)
- b : CO2 emission per kWh (kg CO2 / kWh)

Superchilling and supercooling

Introduction

Fresh foods demand good methods to keep food products at an acceptable low temperature all through the production line, transport and storage. Storage temperature is important in all stages of the products shelf life, and storage by producer, the retailer and the consumer. The market opinion is still that fresh foods are better than frozen foods. Thus, the demand for keeping the food fresh is increasing, and the requirement for keeping the right temperatures are essential. It is therefore important to measure and show that superchilled products with a low content of ice do have the same quality characteristics as fresh products.

Research and development of new and improved methods for chilling have resulted in the concept of superchilling. Literature report has several terms to describe superchilling, including deep chilling, partial chilling, partial freezing and even supercooling (Nordtvedt, 2003). Supercooling is not partly frozen, but chilled under the initial freezing point without ice formation.

Superchilling and supercooling

Superchilling and supercooling have great potential to enable safe, high quality and long term storage of foods without the consumer perceived detrimental effects of freezing. If these technologies were combined with perfusion chilling for meat and fish, then additional benefits such as rapid cooling, low weight loss and novel products could result. Depending on the perfusion fluid there is the potential to cure pork in line or to rapidly chill to a low temperature using a cryoprotectant without actually forming ice crystals. Energy and environmental benefits are envisaged due to reduced heat loads and higher storage temperatures (compared to frozen food).

During superchilling and supercooling factors such as cooling rate and temperature will be of great importance to achieve the defined ice-level (superchilling) ortemperature without freezing (supercooling) in the final product.

The degree of superchilling that will improve the shelf life sufficiently whilst fulfilling the demands regarding process ability and quality attributes need to be determined for the set product groups. Efficient and flexible superchilling processes that preserve premium product quality must be designed and basic data for calculation of chilling time and temperature and refrigeration load must be found. Effective technical tools for measuring the amount and distribution of ice inside the product on-line are required.

Superchilling is a conservation method for foods where some of the water in the food product is frozen. The product is then held at a temperature between -0.5 and -4 °C.

The concept of superchilling has been under continuous development for the last 10 - 20 years. Even today, superchilling of foods is performed in different ways; superchilled storage of foods without any pre treatment and superchilled storage after initial surface freezing followed by temperature equalization.

Figure 1: *Shell freezing of pork neck in impingement freezer for superchilling.*

Practical superchilling methods reported in literature are refrigerated sea water (RSW), air blast tunnels and contact chilling (Winther et al., 2009). During storage, the ice distribution equalizes and the product obtains a uniform temperature at which it is maintained, the ice fraction in the acts as a cold buffer during further storage and transportation (Magnussen et al., 2008). When the temperature is kept at superchilling storage temperatures, there is no need for additional crushed/flaked ice on the fish to keep the temperature low.

Chilled fresh fish is normally packed in boxes filled with approximately 30 % ice to keep the temperature low during transport and storage This addition of ice increases the weight and dimensions of the product to be transported, so reducing efficiency meaning potentially more deliveries and greater fuel use.

Nordtvedt (2003), Duun et al., (2007), Duun et al., (2008), and Stevik et al., (2010) state that superchilling is a method for increasing the shelf life of food products. Several different methods for superchilling have been demonstrated on an experimental basis, and the main effort now is to use the research knowledge on an industrial scale in the food industry. Supercooling has shown high potential for certain kinds of vegetables, and development for supercooling technologies for meat products are now a focus.

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Phase change materials

Introduction

Several reviews have been published in the last ten years about Phase Change Materials (PCM'S). One of the first review has been carried out by (Zalba et al., 2003). In this work a list of available PCM'S from 0°C to 850°C is given, including organic and inorganic, commercial and non-commercial materials. The thermophysical properties listed are the melting temperature, the heat of fusion and the thermal conductivity (mainly liquid). Only one paraffin (tetradecane) is identified in this work as a storage material below 5°C. The most common and the most used phase change material for cooling applications is water. The use of large quantities of chilled water or ice for thermal energy storage has been widely developed for years, especially in air conditioning applications. Many cold storage tanks for building cooling applications have been built and studied. The advantages and drawbacks of the thermal energy storage strategy have been identified through the use of this inexpensive and widely available material. A review on cool thermal storage technologies as a tool for electrical load management was published by (Hasnain, 1998a, b) with a specific study on the pros and cons of the two most common thermal energy storage technologies: chilled water and ice storage. The identified advantages of a system using a cooling storage capacity compared to a conventional one are pointed out by the author:

- a reduction of the refrigeration plant capacity which cas no longer to cope with the peak load
- a 100% load operating condition (at its optimum efficiency) for the chillers plant
- an improvement of the chillers efficiency by operating it during night hours
- a reduction of the refrigerant charge due to the reduction of the refrigerating capacity : this last advantage is of high importance regarding the environmental impact of the refrigerating system

Since it shifts the electricity requirement from peak to off-peak hours, both technologies (chilled water or ice) have demonstrated savings in energy, but also in initial capital costs in the case of large applications. Hasnain also points out the enormous volume requirement of chilled water storage compared to ice storage, and more generally to phase change materials. A suitable phase change temperature is an obvious requirement of a phase change material. The range of temperature corresponding to food cold chain applications is from -60°C (fast freezing processes) to 6°C (fresh food preservation). Other requirements on a phase change material can be grouped in physical, technical and economic requirements:

- large phase change enthalpy
- cycling stability
- small supercooling
- good thermal conductivity
- small volume change during the phase change transition
- chemical stability
- compatibility with other materials
- safety constraints
- low price
- good recyclability

There is not a material fulfilling all those criteria. For low temperatures, usually water-salt solutions at their eutectic concentration are used. Paraffin waxes, fatty acids and sugar alcohols are also potential candidates for cooling applications. Organic, in contrast to nonorganic PCM'S usually show less supercooling or phase separation and, consequently, often eliminate the need for a nucleating agent. But their thermal conductivity and phase change enthalpy are usually lower than water-salt solutions.

PCM Materials implemented in the FRISBEE Tool

PCM name	type	Composition	Tmelt	H (kJ/kg)	density liq	Thermal conductivity liq	Cp liq	URL/Reference
E.00	Salt solution	Water + additive	0.0	334	1.000	0.58	4.19	www.cristopia.com
E.3	Salt solution	Water + sodium carbonate + additives	-3.7	314	1.062	0.6	3.84	www.cristopia.com
E.6	Salt solution	Water + potassium hydrogenocarbonate + additives	-6.0	276	1.115	0.56	3.84	www.cristopia.com
E.11	Salt solution	Water + potassium chloride (~19,5%) + additives	-11.0	303	1.134	0.56	3.33	www.cristopia.com
E.12	Salt solution	Water + urea + additives	-12.0	301	1.092	0.57	3.55	www.cristopia.com
E.15	Salt solution	Water + ammonium chloride + additives	-15.0	303	1.055	0.53	3.87	www.cristopia.com
E.18	Salt solution	Water + sodium nitrate + additives	-18.0	255	1.285	0.56	3.86	www.cristopia.com
E.21	Salt solution	Water + sodium chloride (~22,6% eutectic) + additives	-21.0	233	1.165	0.57	3.35	www.cristopia.com
E.26	Salt solution	Water + sodium chloride + sodium nitrate + additives	-26.0	255	1.249	0.58	3.65	www.cristopia.com
E.29	Salt solution	Water + sodium hydroxide + additives	-29.0	222	1.201	0.64	3.69	www.cristopia.com
E.33	Salt solution	Water + ammonium chloride + sodium nitrate + additives	-33.0	243	1.288	0.56	2.95	www.cristopia.com

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Multi-objective optimization algorithm

Introduction

Low temperature storage is widely employed to increase the storage life of apples. However, the use of refrigeration accounts for up to 15% of the global use of electricity and is also a major contributor to environmental pollution. Increasing the storage temperature by 1°C can significantly reduce the total cost of electricity during apple storage. Several studies have either focused on optimising product quality, Energy use or environmental impact. However, no single study has been performed to simultaneously optimizing all these three parameters. It is generally not possible to obtain a single solution that is optimal for all these objectives, improving one objective usually means degrading others. In tackling such problem, a multi-objective optimization approach can be used. In this approach, a set of solutions that presents the best alternatives, the pareto optimal, is obtained (Deb, 2001; Ehrgott and Gandibleux, 2002). Multi-objective optimization aims at minimizing or maximizing more than two objective functions and may be subject to a set of constrains. In attaining this objective, a decision variables must be defined.

Decision variables

The decision variables are variables that are being changes during the optimization process in order to minimize or maximize the objective functions. For example, in optimizing the quality of a product during refrigerated storage, the control variables may be the initial product quality, the storage temperature, packaging materials etc. As a matter of fact, the decision variables are any variables that can be altered to optimize a particular objective.

The most important control variable in the refrigeration process is the process temperature, and therefore the *temperature* was selected as the Decision variable in the FRISBEE project for optimization of a particular technology.

Objective functions

The objective functions are the functions that is to be optimized in the optimization problem. They can idea be algebraic or differential equations, and must be a function of the decision variable (i.e. in this case, they must be a function of temperature). In principle, the can be any number of objective functions in an multi-objective optimization process. However, the complexity of the optimization process increases with the addition of more objective functions. In practice, the number of objective functions should be limited to 3, and it because impractical to interpret the results graphically when the number of objective functions is greater than 3.

In developing the multi-objective optimization algorithm in this study, the main objective functions were identified as the models for energy use, CO_2 emission and quality loss. These models were developed in D.3.2.1.5 and D.3.2.4.9. The software is developed in such a way that a user can select any two or all three of the different objective functions. For the quality evolution, the user will have to define (by selecting) which quality indicators will be used for the optimization problem.

Constraints

The best solutions may not usually be the most practical. For instance, the optimal storage temperature of a freezing process might be -90°C, but the power of the compressor might not allow the temperature to go below -30°C. Another example is apple storage, where storing at sub-zero

temperatures might suggest better firmness, but that will also mean the apples will suffer from chilling injury (Watkins and Jackie Nock, 2004). This means therefore that, for every optimization problem, there are certain constraints may be defined.
Constraints may be defined on the decision variables (as bound constraints) or directly on the objective functions. In this study, the constraints are only defined as temperature bounds.

Weighted multi-objective function

Product quality, energy use and CO_2 emission are three objectives that are contrasting in that minimising losses in product quality will most often require storing at lower temperatures, which will result in a higher energy usage and emission of CO_2. This means that no single solution might be considered optimal, but a set of optimal solutions (pareto optimal) are possible.
To get that unique optimal solution, taking into account trade-offs in all three objectives, we defined a weighted multi-objective function by assigning different weights to product quality, energy use and environmental impact. The following guidelines were used:

- € values (±) are assigned to each objective, since all three objectives can be expressed in terms of €.
    - For the product quality, a price (€ / kg) is assigned, and this may vary from one quality grade to another. Critical quality limits are provided, beyond which it is assumed the product has no value.
    - Energy is assigned a cost (€ / kWh) based on the electricity pricing.
    - Emission is a assigned a cost (€ / ton of CO_2 emitted) based on the emission rights.
- A user can altogether eliminate one or more objective function(s), meaning he/she has literally assigned a zero weight to this objective function(s), if he/she wishes to do so.

The weighted objective function is the following, which calculates the "chain profit":

$$
\begin{aligned}
&if \quad \mathrm{Q}_{\mathrm{product}} \geq \mathrm{Q}_{\mathrm{product}_{\mathrm{crit}}} \\
&\qquad f_{\mathrm{profit}} = U_{\mathrm{product}} - E_{\mathrm{use}} U_{electricity} - CO_{2,\mathrm{emission}} U_{emission\ rights} \\
&else \\
&\qquad f_{\mathrm{profit}} = 0 - E_{\mathrm{use}} U_{electricity} - CO_{2,\mathrm{emission}} U_{emission\ rights} \\
&end
\end{aligned}
\tag{1}
$$

where f_{profit} (€ / kg) is the cold chain block profit; U_{product} (€ / kg) is the unit price of the product; E_{use} (kWh / kg) is the energy use in cooling, $U_{electricity}$ (€ / kWh) is the electricity pricing, $CO_{2,\mathrm{emission}}$ (kg CO2 / kg) is the CO2 emission and $U_{emission\ rights}$ (€ / kg CO2) and is the expected cost from the emission of CO_2 to the environment (CO_2 emission rights).

References

- Deb, K., 2001. Multi-objective Optimization using Evolutionary Algorithms (Chichester: John Wilet & Sons).
- Ehrgott, M. and Gandibleux, X. (Eds), 2002. Multiple Criteria Optimization – State-of-the-art Annotated Bibliographic Surveys (Dordrecht, Kluwer Academic Publisher).